# THERMAL EXPANSION OF HEAT-RESISTING ALLOYS: NICKEL-CHROMIUM, IRON-CHROMIUM, AND NICKEL-CHROMIUM-IRON ALLOYS

By Peter Hidnert


ABSTRACT

This paper gives data on the linear thermal expansion of various heat-resisting alloys (nickel-chromium, iron-chromium, and nickel-chromium-iron alloys). The alloys contain 0 to 77 per cent nickel, 5 to 27 per cent chromium, and 0 to 82 per cent iron.

The coefficients of expansion of the alloys were determined for various temperature ranges between 20° and 1,000° C., and the effects due to temperature, chemical composition, heat treatment, etc., were determined. Critical regions were located on the thermal expansion curves of some of the alloys.

For a given temperature range, the coefficients of expansion of nickel-chromium alloys containing from 0 to about 20 per cent chromium are nearly the same.

The effects of chromium content, carbon content, heat treatment, etc., on the coefficients of expansion of iron-chromium alloys for various temperature ranges are indicated in a figure.

The results on the thermal expansion of nickel-chromium-iron alloys were correlated with the structure of the alloys. Transformations from one phase to another caused significant changes in thermal expansion. The expansion curves on the first heating of nearly all of the cast nickel-chromium-iron alloys indicate a retardation or decrease in expansion between 700° and 800° C., due to precipitation of carbide. The effects of change of composition on the coefficients of expansion of both cast and annealed nickel-chromium-iron alloys are indicated.

The table in the summary gives a comparison of the coefficients of expansion of the three groups of alloys.


CONTENTS



## I. INTRODUCTION

In November, 1927, after a manuscript on the thermal expansion of alloys of the "stainless iron" type [1] was completed, A. P. Spooner, engineer of tests of the Bethlehem Steel Co., Bethlehem, Pa., pointed out the many applications of the alloys of nickel and chromium for both heat and rust resisting service and suggested that it might be well for the National Bureau of Standards to consider some work on the thermal expansion of these compositions in the same manner in which the work on stainless iron had been carried out. In accordance with this suggestion, an investigation on the thermal expansion of such alloys was planned.

[1] P. Hidnert and W. T. Sweeney, B. S. Sci. Paper No. 570 1928.

The bureau secured 35 commercial heat-resisting alloys of various types through the cooperation of 10 companies.[2] The alloys supplied by these companies contain 0 to 77 per cent nickel, 5 to 27 per cent chromium, 0 to 82 per cent iron, and other elements generally in small amounts. The alloys were divided into three groups: Nickel-chromium alloys, iron-chromium alloys, and nickel-chromium-iron alloys.

The coefficients of expansion of the alloys were determined for various temperature ranges between 20° and 1,000° C., and the effects due to temperature, chemical composition, heat treatment, etc., were determined. Critical regions were located on the thermal expansion curves of some of the alloys. These data will be useful to physicists, engineers, metallurgists, and others in the application of these alloys;

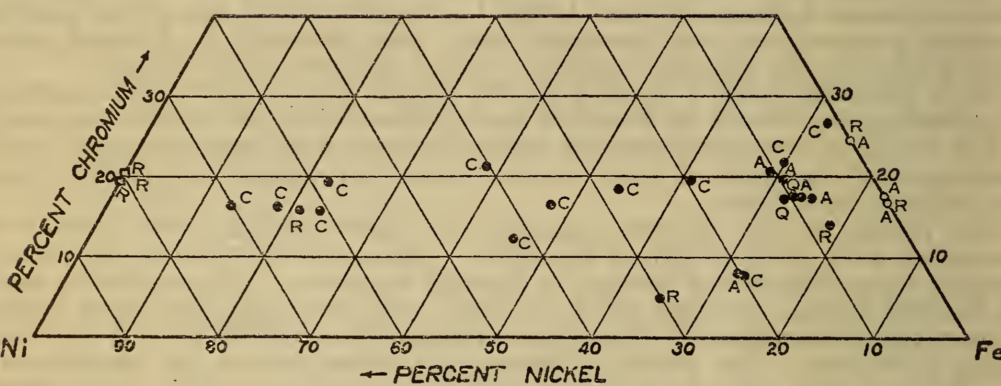


Figure 1.—*Portion of ternary diagram showing the chemical composition of the heat-resisting alloys investigated*

| | |
|---|---|
| □=Ni-Cr. | A=Annealed. |
| ○=Fe-Cr. | C=Cast. |
| ●=Ni-Cr-Fe. | Q=Quenched. |
| | R=Hot-rolled. |

for example, in the design of equipment for modern high-temperature processes.

## II. MATERIALS INVESTIGATED

Thirty-five samples of various heat-resisting alloys (nickel-chromium, iron-chromium, and nickel-chromium-iron alloys) were investigated. Table 1 gives the commercial names, chemical compositions, heat treatments, names of manufacturers, etc. The relative locations of these samples on the ternary diagram of the nickel-chromium-iron system are shown in Figure 1. Three of the samples are binary nickel-chromium alloys, 6 are binary iron-chromium, and the remaining 26 samples are ternary alloys.

The samples used for thermal expansion determinations were approximately 299 mm in length and 6 to 13 mm in diameter (or diagonal if square or rectangular cross section).

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[2] The author wishes to express his appreciation for the cooperation by Bethlehem Steel Co., Bethlehem, Pa.; Calorizing Co., Pittsburgh, Pa.; Cyclops Steel Co., Titusville, Pa.; Driver-Harris Co., Harrison, N. J.; Gilby Wire Co., Newark, N. J.; Hoskins Manufacturing Co., Detroit, Mich.; Ludlum Steel Co., Watervliet, N. Y.; Michiana Products Corporation, Michigan City, Ind.; Ohio Steel Foundry Co., Lima, Ohio; and Republic Steel Corporation, Youngstown, Ohio. These companies furnished the samples of heat-resisting alloys and information about the preparation.

| Sample | Commerc | | Remarks by manufacturer |
|---|---|---|---|
| 1292 [3] | Chromel A | ring | Used as heating elements for high-temperature electric furnaces or other heating devices. |
| 1293 | Nichrome IV | | |
| 1402 [3] | Tophet A | | |
| 1294 | Cimet | | |
| 1299 | Calite S | | Immunity from oxidation up to 1,650° F. Not affected by weather corrosion or by corrosion with nitric acid, sulphur compounds, alkaline solutions, and many organic acids. |
| 1300 | do | | Do. |
| 1300A [5] | do | | |
| 1427 [6] | Stainless iron | | |
| 1428 [6] | No.74 heat-re | | |
| 1291 [3] | Alloy 502 | ring | Used very extensively in the heat-resisting field for all kinds of castings, such as furnace rails, pots, and supports. |
| 1295 | | | Intended for general heat enduring applications up to 2,000° F. Resistant to corrosion in contact with ordinary products of combustion. |
| 1296 | Calite B | | Intended for heat enduring applications up to 1,800° F. Developed for the fabrication of beams and other parts required to sustain loads at high temperatures. Resistant to corrosion in contact with ordinary products of combustion. |
| 1296A [5] | Calite B | | |
| 1297 | Calite E | | Immunity from oxidation up to 1,800° F. Not affected by weather corrosion, sulphur compounds, and many organic and inorganic salts. |
| 1298 | Calite N | | Immune to oxidation up to 2,000° F. |
| 1301 | No. 1 alloy | Cor- | For high temperature. |
| 1302 | No. 2 alloy | | For medium temperature not in excess of 1,900° F. |
| 1303 [7] | No. 4 alloy | | |
| 1304 [8] | Fahrite N-1 | o | Distinguished for its resistance to oxidation and corrosion and its unusually great strength at elevated temperature. Recommended principally for the following: Carbonizing boxes, retorts, furnace parts, disks for open annealing furnaces, domestic and industrial oil burning equipment, tube supports, and all parts used in temperatures ranging from 1,000° to 2,200° F. |
| 1305 | Nichrome | | |
| 1306 | Chromax | | |
| 1306A [5] | Chromax | | |
| 1310 | Cyclops 17A | | |
| 1311 [8] | Uniloy-specia | | |
| 1312 [8] | Uniloy 21-12 | | |
| 1313 [3] | Cast chromel | ing | |
| 1314 [8] | Fahrite CS | o | |
| 1314A [5] | Fahrite CS | | |
| 1403 [8] | Tophet C | | |
| 1404 [8] | Chromin D | | |
| 1411 [9, 10] | Special CNS | | Valve steel. |
| 1411A [5] | Special CNS | | |
| 1418 [9, 11] | Enduro KA2 | tion | Chief application for sulphite pulp mill equipment. |
| 1419 | Nirosta KA-2 | | |
| 1424 [9] | Nirosta KA-2 | | |

[1] All values for chemic
samples, except those indic . C. Redmond, of the Bureau of Standards.
[2] Information furnished J. C. Redmond, of the Bureau of Standards. Contents of other
[3] Chemical analysis by
[4] By difference.
[5] Duplicate sample.
[6] Chromium and carbo
from manufacturer's heat a

TABLE 1.—*Chemical composition and heat treatment of heat-resisting alloys*

(a) NICKEL-CHROMIUM ALLOYS

| Sample | Commercial name | Chemical composition [1] | | | | | | | | | | Heat treatment [2] | Manufacturer | Remarks by manufacturer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Nickel | Chromium | Iron | Manganese | Silicon | Carbon | Aluminum | Copper | Phosphorus | Sulphur | | | |
| | | *Per cent* | *Per cent* | *Per cent* | *Per cent* | *Per cent* | *Per cent* | *Per cent* | *Per cent* | *Per cent* | *Per cent* | | | |
| 1292 [3] | Chromel A | 77.0 | 19.3 | 0.65 | 2.50 | 0.12 | 0.08 | <0.1 | <0.1 | | | Hot-rolled and allowed to cool slowly | Hoskins Manufacturing Co. | Used as heating elements for high-temperature electric furnaces or other heating devices. |
| 1293 | Nichrome IV | [4] 76.80 | 20.40 | .40 | 1.92 | .26 | .12 | | .10 | | | Hot-rolled | Driver-Harris Co. | |
| 1402 [8] | Tophet A | 77.0 | 19.6 | .45 | 2.14 | .13 | .13 | <.1 | <.1 | | | do | Gilby Wire Co. | |
| **(b) IRON-CHROMIUM ALLOYS** | | | | | | | | | | | | | | |
| 1294 | Cimet | 0.00 | 24.63 | [4] 74.08 | 0.02 | 0.27 | 0.16 | | 0.24 | | | Hot-rolled | Driver-Harris Co. | |
| 1299 | Calite S | Trace. | 17.04 | 81.74 | .28 | .62 | .04 | 0.08 | .14 | | | do | Calorizing Co. | Immunity from oxidation up to 1,650° F. Not affected by weather corrosion or by corrosion with nitric acid, sulphur compounds, alkaline solutions, and many organic acids. |
| 1300, 1300A [5] | do | .01 | 17.08 | 81.74 | .45 | .58 | .06 | .08 | | | | Annealed for 30 minutes at 1,450° F. and air cooled. | do | Do. |
| 1427 [6] | Stainless iron type C 2 | .08 | 17.6 | [4] 81.7 | .29 | .28 | .04 | | | 0.021 | 0.021 | Annealed at 1,450° F. and cooled in furnace. | Bethlehem Steel Co. | |
| 1428 [6] | No. 74 heat-resisting steel | .07 | 24.6 | [4] 74.0 | .27 | .29 | .74 | | | .014 | .017 | Annealed at 1,680° F. and cooled in furnace. | do | |
| **(c) NICKEL-CHROMIUM-IRON ALLOYS** | | | | | | | | | | | | | | |
| 1291 [3] | Alloy 502 | 40.3 | 21.1 | [4] 34.6 | 1.43 | 1.91 | 0.44 | <0.1 | 0.1 | | | Cast in green or bake sand at 2,550° to 2,700° F. | Hoskins Manufacturing Co. | Used very extensively in the heat-resisting field for all kinds of castings, such as furnace rails, pots, and supports. |
| 1295 | | 27.78 | 18.50 | 50.30 | .63 | 1.90 | .58 | .08 | | | | Cast at about 2,750° F. | Calorizing Co. | Intended for general heat enduring applications up to 2,000° F. Resistant to corrosion in contact with ordinary products of combustion. |
| 1296, 1296A [5] | Calite B | 8.41 | 21.66 | 64.63 | 1.16 | 1.24 | 1.15 | 1.57 | .10 | | | do | do | Intended for heat enduring applications up to 1,800° F. Developed for the fabrication of beams and other parts required to sustain loads at high temperatures. Resistant to corrosion in contact with ordinary products of combustion. |
| 1297 | Calite E | 7.80 | 17.28 | 73.62 | .45 | .28 | .14 | .18 | .14 | | | Hot-rolled and cooled in brine. Annealed at 2,000° F. for 1 hour and air cooled. | do | Immunity from oxidation up to 1,800° F. Not affected by weather corrosion, sulphur compounds, and many organic and inorganic salts. |
| 1298 | Calite N | 58.07 | 19.12 | 19.21 | .94 | 1.69 | .54 | .03 | .13 | | | Cast at about 2,750° F. | do | Immune to oxidation up to 2,000° F. |
| 1301 | No. 1 alloy | 65.22 | 16.23 | 15.33 | 1.40 | 1.18 | .59 | | | | | Cast | Michiana Products Corporation. | For high temperature. |
| 1302 | No. 2 alloy | 41.98 | 12.12 | 44.10 | .55 | .81 | .43 | | | | | do | do | For medium temperature not in excess of 1,900° F. |
| 1303 [7] | No. 4 alloy | 19.80 | 7.76 | 69.30 | .32 | 1.03 | .49 | | | | | do | do | |
| 1304 [5] | Fahrite N-1 | 36.0 | 16.4 | [4] 45.4 | .71 | 1.03 | .42 | | | | | Cast in sand mold at 2,850° to 2,900° F. | Ohio Steel Foundry Co. | Distinguished for its resistance to oxidation and corrosion and its unusually great strength at elevated temperature. Recommended principally for the following: Carbonizing boxes, retorts, furnace parts, disks for open annealing furnaces, domestic and industrial oil burning equipment, tube supports, and all parts used in temperatures ranging from 1,000° to 2,200° F. |
| 1305 | Nichrome | 61.00 | 15.70 | [4] 20.26 | .62 | .69 | .95 | | .78 | | | Cast at about 2,750° F. | Driver-Harris Co. | |
| 1306, 1306A [5] | Chromax | 19.55 | 19.55 | [4] 58.93 | .15 | .09 | 1.25 | | .48 | | | Cast at about 2,825° F. | do | |
| 1310 [illegible] | Cyclops 17A | 20.2 | 7.9 | [4] 69.6 | .74 | 1.12 | .39 | | | | | Forged at 2,050° to 1,800° F. under a hammer from an 8-inch square ingot to ⅜ inch square; annealed at 1,600° to 1,650° F. | Cyclops Steel Co. | |
| 1311 [5] | Uniloy-special 18-8 | 9.7 | 19.7 | [4] 69.3 | .24 | .89 | .21 | | | | | do | do | |
| 1312 [5] | Uniloy 21-12 | 10.4 | 20.7 | [4] 67.5 | .62 | .56 | .18 | | | | | do | do | |
| 1313 [3] | Cast chromel | 70.1 | 16.3 | 6.6 | 3.23 | 2.51 | .94 | <.1 | <.1 | | | Cast in green sand at about 2,700° F. | Hoskins Manufacturing Co. | |
| 1314 [9], 1314A [5] | Fahrite CS | 1.3 | 26.7 | [4] 70.0 | .57 | .66 | .72 | | | | | Cast in sand mold at 2,850° to 2,900° F. | Ohio Steel Foundry Co. | |
| 1403 [8] | Tophet C | 63.0 | 15.9 | [4] 18.1 | 2.14 | .78 | .08 | | | 0.013 | | Hot-rolled | Gilby Wire Co. | |
| 1404 [8] | Chromin D | 30.1 | 4.9 | [4] 63.9 | .64 | .22 | .20 | | | .013 | | do | do | |
| 1411 [9, 10], 1411A [5] | Special CNS Steel | 7.5 | 14.0 | [4] 74.7 | .17 | 2.40 | .30 | | | .014 | 0.012 | do | Ludlum Steel Co. | Valve steel. |
| 1418 [9, 11] | Enduro KA2 Mo | 8.9 | 17.5 | [4] 69.6 | .41 | .37 | .12 | | | .017 | .016 | Hot-rolled and annealed | Republic Steel Corporation. | Chief application for sulphite pulp mill equipment. |
| 1419 | Nirosta KA-2 | 10.80 | 17.34 | [4] 71.19 | | .61 | .06 | | | | | Quenched in water from approximately 2,000° F. | Ludlum Steel Co. | |
| 1424 [9] | Nirosta KA-2S | 9.6 | 17.7 | [4] 72.0 | .36 | .28 | .06 | | | .016 | .012 | Quenched in water from 1,975° F. | do | |

[1] All values for chemical composition, were obtained by manufacturers on specimens cut from the ends of the investigated samples, except those indicated otherwise.
[2] Information furnished by manufacturer.
[3] Chemical analysis by J. C. Redmond, of the Bureau of Standards.
[4] By difference.
[5] Duplicate sample.
[6] Chromium and carbon contents determined by J. C. Redmond, of the Bureau of Standards. Contents of other elements from manufacturer's heat analysis.
[7] Vanadium 0.46 per cent.
[8] Nickel, chromium, and carbon contents determined by J. C. Redmond, of the Bureau of Standards.
[9] Nickel, chromium, and carbon contents determined by J. C. Redmond, of the Bureau of Standards. Contents of other elements from manufacturer's heat or ladle analysis.
[10] Tungsten 0.89 per cent.
[11] Molybdenum 3.08 per cent.

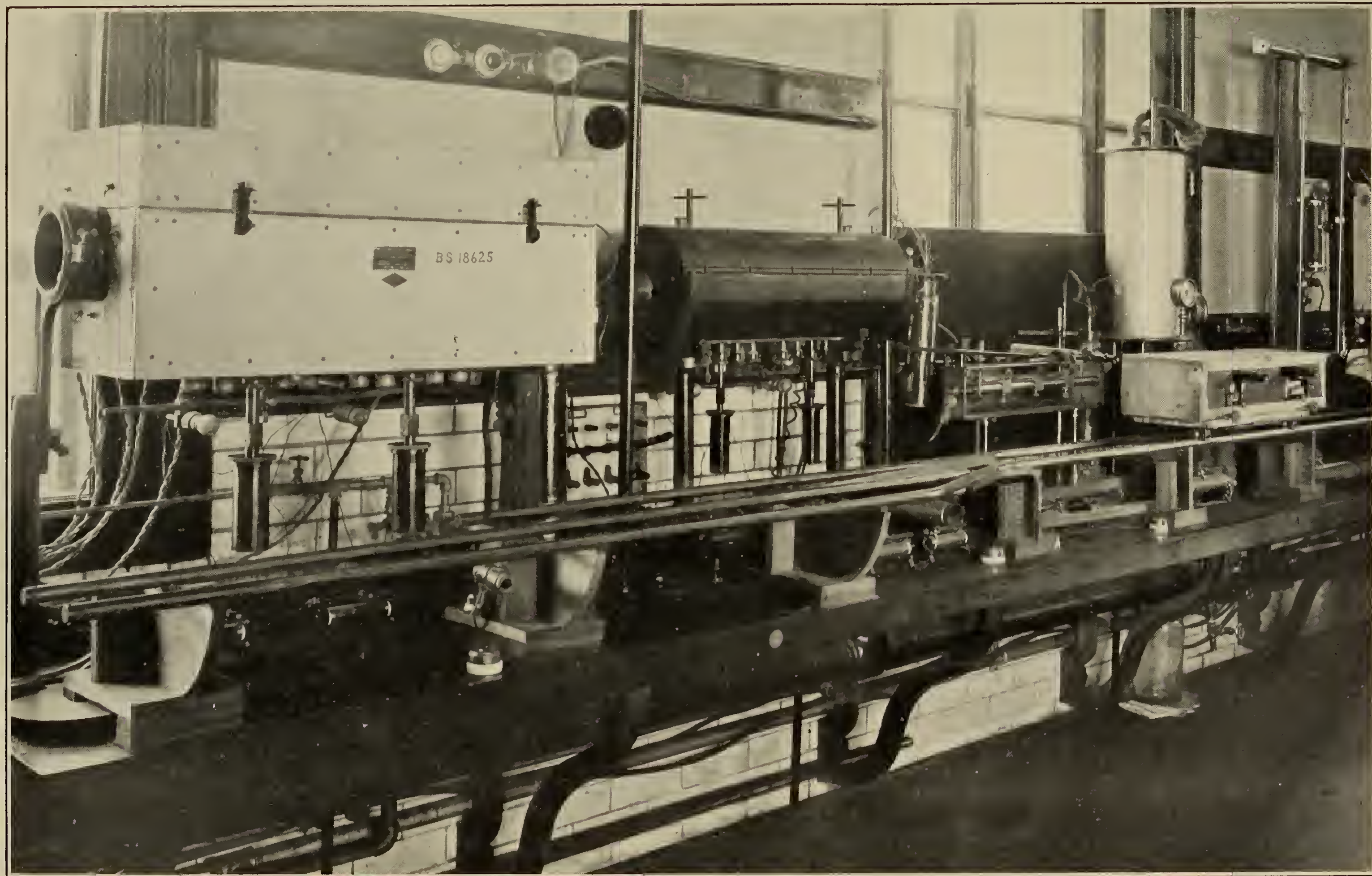



FIGURE 2.—*Part of thermal expansion apparatus*

## III. APPARATUS

Figure 2 shows part of the apparatus used in this investigation. With this equipment it is possible to determine the linear thermal expansion of solids at various temperatures between −150° and +1,000° C.

The white furnace shown at the left of Figure 2 was used for temperature ranges between room temperature and 1,000° C. This furnace was employed in the tests on all of the alloys in this investigation (except the third test on sample 1296A). The observation wires were suspended from sharp V grooves near the ends of the sample as shown in Figure 5 of Scientific Paper of the Bureau of Standards No. 524. This publication gives a detailed description of the apparatus.

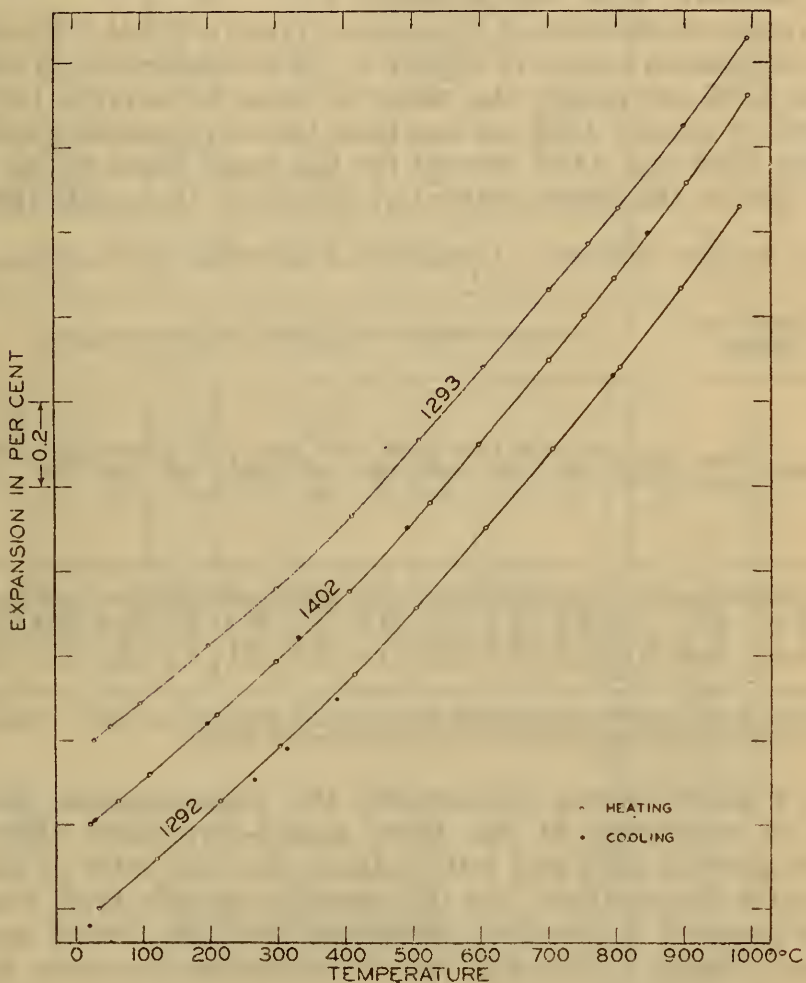



FIGURE 3.—*Linear thermal expansion of three hot-rolled nickel-chromium alloys*

1292, Ni 77.0, Cr 19.3, Mn 2.50, C 0.30, Fe 0.65, Si 0.12, Al < 0.1 Cu < 0.1 per cent.
1402, Ni 77.0, Cr 19.6, Mn 2.14, C 0.13, Fe 0.45, Si 0.13, Al < 0.1 Cu < 0.1 per cent.
1293, Ni 76.80, Cr 20.40, Mn 1.92, C 0.12, Fe 0.40, Si 0.26, Cu 0.10 per cent.

## IV. EXPERIMENTAL AND DERIVED RESULTS

The 35 samples of heat-resisting alloys were classified into three groups as indicated in Section II. In all cases the coefficients of expansion were derived from the observations on heating except when

indicated otherwise. The expansion curves in some figures are plotted from different origins to display the individual characteristics of each curve.

### 1. NICKEL-CHROMIUM ALLOYS

In this group there are three samples of hot-rolled nickel-chromium alloys containing 77 per cent nickel and about 2 per cent manganese. The chemical composition, heat treatment, and other information about the samples have been given in Table 1.

Figure 3 shows the observations obtained on the three samples of nickel-chromium alloys. The linear thermal expansion appears to increase regularly with temperature.

The average coefficients of expansion given in Table 2 were derived from the expansion curves of Figure 3. The coefficients of expansion of sample 1292 are nearly the same as those for sample 1402. The coefficients of sample 1293 are less than the corresponding coefficients of samples 1292 and 1402 (except for the range from 20° to 60° C.), probably due to the larger content of chromium in sample 1293.

TABLE 2.—*Average coefficients of expansion of hot-rolled nickel-chromium alloys* [1]

| Sample | Chemical composition | | Average coefficients of expansion per degree centigrade | | | | | | | | | | | Change in length due to heat treatment received during test |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nickel | Chromium | 20° to 60° C. | 20° to 100° C. | 20° to 200° C. | 20° to 300° C. | 20° to 400° C. | 20° to 500° C. | 20° to 600° C. | 20° to 700° C. | 20° to 800° C. | 20° to 900° C. | 20° to 1,000° C. | |
| | *Per cent* | *Per cent* | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | *Per cent* |
| 1292 | 77.0 | 19.3 | ------ | 13.6 | 14.0 | 14.3 | 14.5 | 15.1 | 15.6 | 16.1 | 16.5 | 17.0 | 17.6 | −0.02 |
| 1402 | 77.0 | 19.6 | 13.1 | 13.3 | 13.8 | 14.0 | 14.4 | 15.0 | 15.7 | 16.2 | 16.7 | 17.2 | 17.8 | +.00 |
| 1293 | 76.80 | 20.40 | 13.8 | 13.0 | 13.3 | 13.3 | 13.9 | 14.7 | 15.3 | 15.8 | 16.2 | 16.7 | 17.2 | |

[1] This table also gives the differences in length before and after the expansion tests. The plus (+) sign indicates an increase in length and the minus (−) sign a decrease in length.

Figure 4 shows curves representing the instantaneous coefficients or rates of expansion of the three nickel-chromium alloys. The curves for samples 1292 and 1402 indicate that the rates of expansion increase with temperature, but the curve for sample 1293, which contains the greatest amount of chromium and the lowest amount of manganese, shows a retarded rate of expansion between 600° and 800° C.

Table 3 gives a summary of the coefficients of expansion obtained by various observers, including the values obtained by the present author. These coefficients of expansion refer to various nickel-chromium alloys containing from 0 to 80 per cent chromium. The treatments (cast, wrought, hot rolled and annealed) are indicated in the table. Coefficients of expansion obtained by Hidnert [3] on nickel are included in the table. For a given temperature range, the coefficients of expansion of alloys containing from 0 to about 20 per cent chromium are nearly the same.

[3] L. Jordan and W. H. Swanger, B. S. Research Paper No. 257; 1930.

TABLE 3.—*Summary of coefficients of expansion of nickel-chromium alloys*

| Sample | Chemical composition | | Treatment | Average coefficients of expansion per degree centigrade | | | | | | | | | | Observer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nickel | Chromium | | Room temperature to 100° C. | 20° to 200° C. | Room temperature to 300° C. | 20° to 400° C. | 20° to 500° C. | Room temperature to 600° C. | 20° to 700° C. | 20° to 800° C. | 20° to 900° C. | 20° to 1,000° C. | |
| | *Per cent* | *Per cent* | | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 11^{-6}$ | |
| 2806F | 100 | ------ | Cast | 14.9 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | [1] 17.6 | Dean.[2] |
| B-2 | 99.94 | ------ | Annealed [3] | 13.3 | ------ | 14.4 | ------ | ------ | 15.5 | ------ | ------ | 16.3 | ------ | Hidnert.[4] |
| ([5]) | ------ | 10 | | 13.3 | 13.8 | 14.2 | 14.6 | 15.0 | 15.5 | 15.9 | 16.4 | 16.8 | ------ | Chevenard.[6] |
| | 85 | 15 | Wrought | [7] 13.2 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ([8]). |
| | 85 | 15 | do | [7] 13.5 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ([8]). |
| | 85 | 15 | do | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 16 | ([8]). |
| 1292 | 77.0 | 19.3 | Hot-rolled | 13.6 | 14.0 | 14.3 | 14.5 | 15.1 | 15.6 | 16.1 | 16.5 | 17.0 | 17.6 | Hidnert.[9] |
| 1402 | 77.0 | 19.6 | do | 13.3 | 13.8 | 14.0 | 14.4 | 15.0 | 15.7 | 16.2 | 16.7 | 17.2 | 17.8 | Do.[9] |
| | 80 | 20 | Wrought | [7] 13.2 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ([8]). |
| | 80 | 20 | do | [7] 13.5 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ([8]). |
| | 80 | 20 | do | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 16 | ([8]). |
| 1293 | 76.8 | 20.4 | Hot-rolled | 13.0 | 13.3 | 13.3 | 13.9 | 14.7 | 15.3 | 15.8 | 16.2 | 16.7 | 17.2 | Hidnert.[9] |
| 2833F | 74.7 | 23.8 | Cast | 13.5 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | [1] 17.7 | Dean.[2] |
| 2834F | 50.5 | 47.7 | do | 13.5 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | [1] 17.7 | Do.[2] |
| 2835F | 25 | 75 | do | 10.3 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | [1] 13.1 | Do.[2] |
| 2852F | 20 | 80 | do | 8.9 | ------ | ------ | ------ | ------ | ------ | ------ | ------ | ------ | [1] 12.4 | Do.[2] |

[1] Computed in 1931 from the published data of observer.
[2] Rensselaer Polytechnic Institute, Engineering and Science Series, No. 26; 1930.
[3] Before expansion determinations were made, sample was annealed at 950° C. for one hour and cooled in furnace. (This fact was not reported in publication mentioned in footnote 4.)
[4] L. Jordan and W. H. Swanger, B. S., Research Paper No. 257; 1930.
[5] Coefficients of expansion computed in 1931 from equation given by observer.
[6] Comptes Rendus, vol. 164, p. 916; 1917; and Revue de Métallurgie, vol. 14, p. 610; 1917.
[7] From 0 to 100° C.
[8] Data furnished by manufacturer of alloy (Proc. Am. Soc. Testing Materials, vol. 24, p. 189; 1924).
[9] Present investigation.

## 2. IRON-CHROMIUM ALLOYS

In the present investigation six samples of iron-chromium alloys containing from 17.0 to 24.6 per cent chromium were used. The chemical composition, heat treatment, and other information about these samples have been given in Table 1.

Figures 5 to 9, inclusive, show the observations obtained. Slight transformations were located on all samples except samples 1299 and 1294. The arrows in Figures 6 to 8 indicate the beginning of the

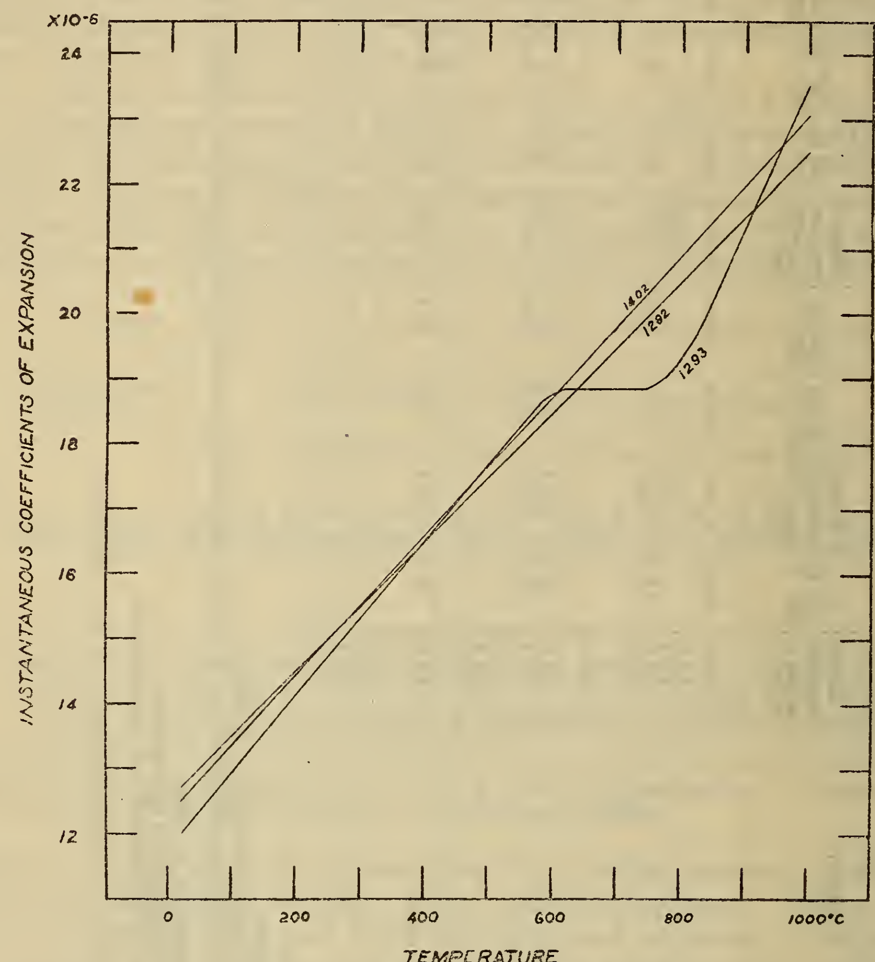



FIGURE 4.—*Instantaneous coefficients of expansion of three hot-rolled nickel-chromium alloys*

transformation. The dotted portions of the curves of samples 1299 and 1294 indicate that sufficient observations were not obtained between 900° and 1,000° C. to determine the presence or absence of transformations.

One of the following temperatures may be taken for the temperature of the beginning of the transformation or critical region on heating:

1. The temperature at which the rate of expansion (or instantaneous coefficient of expansion) of the sample begins to decrease.
2. The temperature at which the sample begins to contract. (At this temperature the rate of expansion is generally zero.)

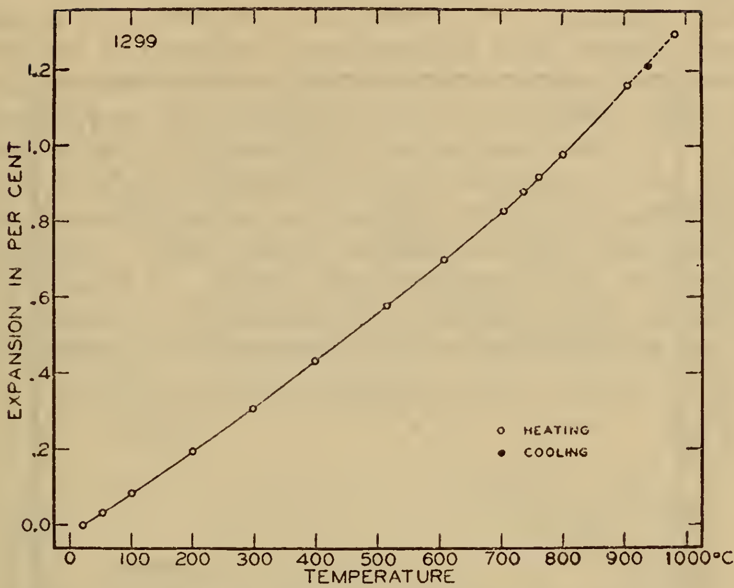



FIGURE 5.—*Linear thermal expansion of hot-rolled iron-chromium alloy*

Fe 81.74, Cr 17.04, C 0.04, Mn 0.28, Si 0.62, Ni trace, Al 0.08, Cu 0.14 per cent.

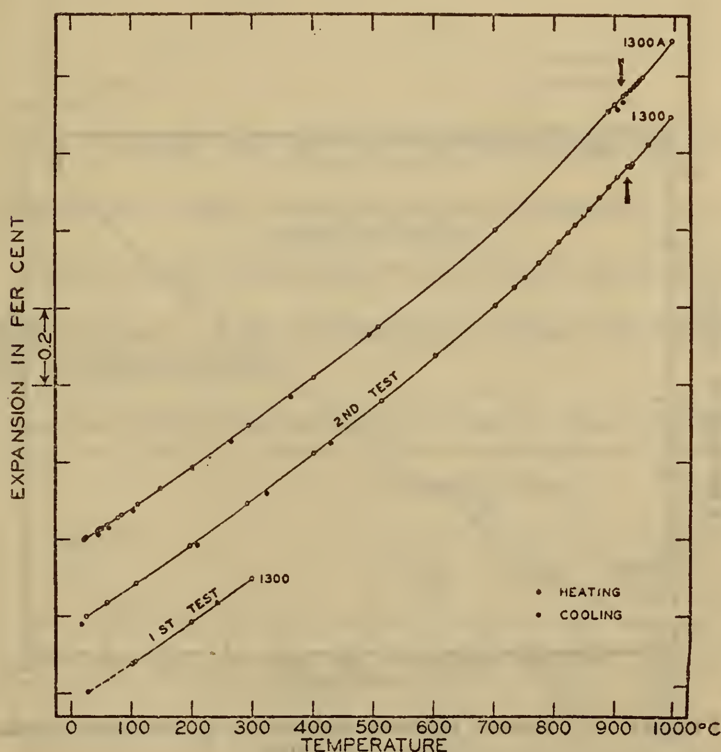



FIGURE 6.—*Linear thermal expansion of two samples of annealed iron-chromium alloy*

Fe 81.74, Cr 17.68, C 0.06, Mn 0.45, Si 0.58, Ni 0.01, Al 0.08 per cent.

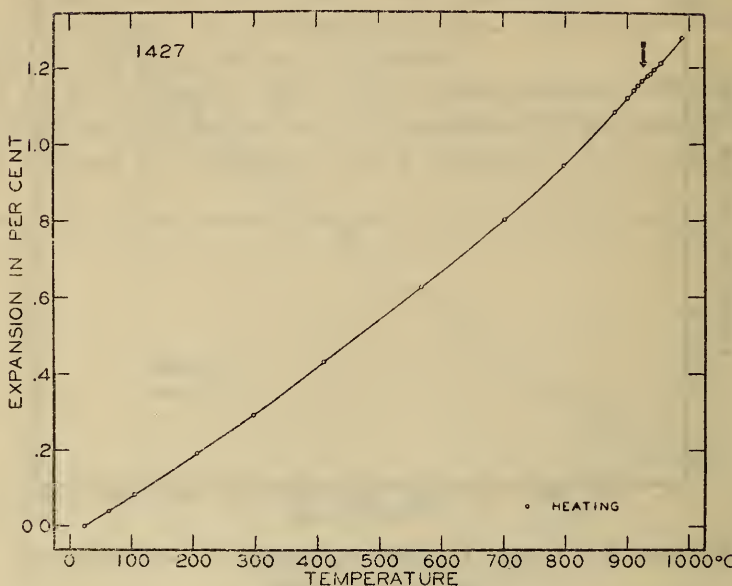



FIGURE 7.—*Linear thermal expansion of annealed iron-chromium alloy*

Fe 81.7, Cr 17.6, C 0.04, Mn 0.29, Si 0.28, Ni 0.08, P 0.021, S 0.021 per cent.

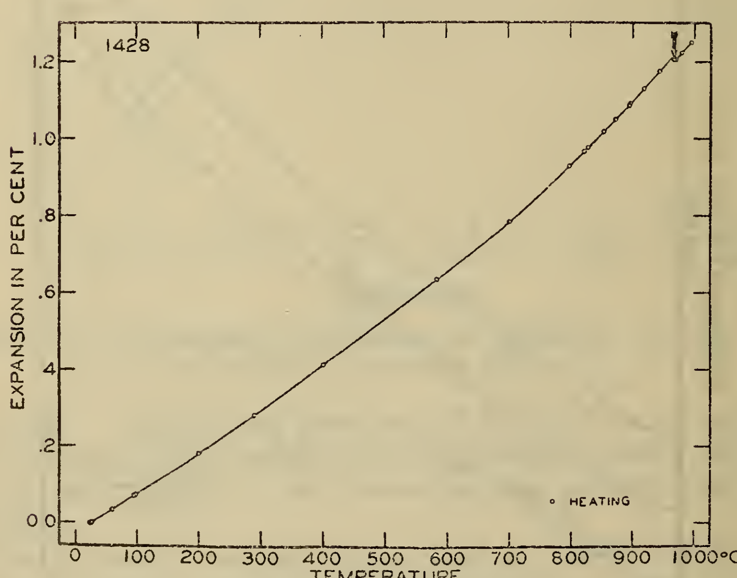



FIGURE 8.—*Linear thermal expansion of annealed iron-chromium alloy*

Fe 74.0, Cr 24.6, C 0.74, Mn 0.27, Si 0.29, Ni 0.07, P 0.014, S 0.017 per cent.

In this and preceding publications, the author has generally selected the second temperature for the temperature of the beginning of the transformation on heating. In case the expansion curve of the sample does not indicate contraction but only retardation, the temperature of the beginning of the transformation has been taken as the temperature on the expansion curve (not the curve of the rate of expansion) where irregularity in expansion begins. The temperature of the end of the transformation on heating, and the temperatures of the transformation on cooling were determined similarly.

Data relating to the critical regions of four samples on heating are given in Table 4. These data indicate that an increase in the chromium content of iron-chromium alloys (17.1 to 24.6 per cent chromium) causes an increase in the temperature at which the

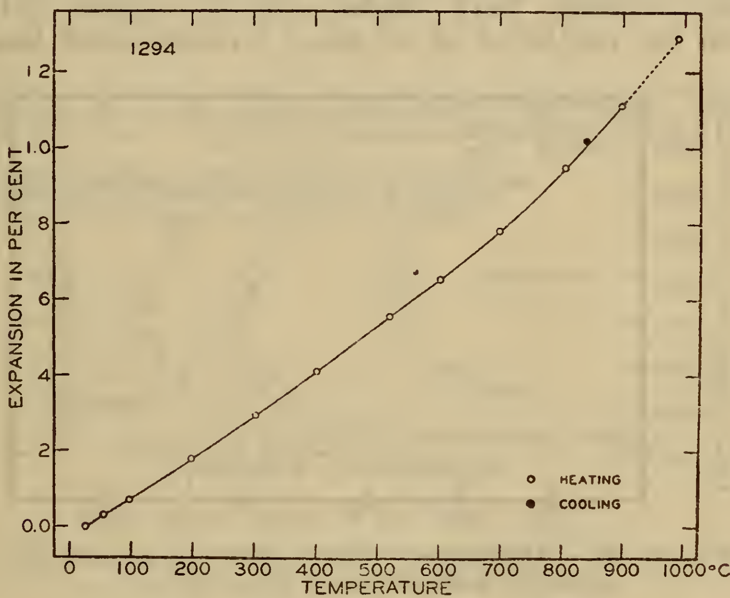



FIGURE 9.—*Linear thermal expansion of hot-rolled iron-chromium alloy*

Fe 74.08, Cr 24.63, C 0.16, Mn 0.62, Si 0.27, Ni 0.00, Cu 0.24 per cent.

critical region occurs. The contraction during the transformation is very small for these alloys.

TABLE 4.—*Critical regions of iron-chromium alloys on heating*

| Sample | Chemical composition | | Critical region | | |
|---|---|---|---|---|---|
| | Chromium | Carbon | Beginning | End | Contraction |
| | *Per cent* | *Per cent* | °*C.* | °*C.* | *Per cent* |
| 1300 [1] | 17.1 | 0.06 | 918 | 924 | 0.002 |
| 1300A | 17.1 | .06 | 910 | (?) | .000 |
| 1427 | 17.6 | .04 | 925 | 930 | .000 |
| 1428 | 24.6 | .74 | 964 | 970 | .005 |

[1] Second test.

The critical regions are due to transformations from alpha phase into gamma phase (austenite). Bain[4] showed a diagram (fig. 10)

[4] E. C. Bain, Transactions of American Society for Steel Treating, vol. 9, p. 9; 1926.

of the austenite region in iron-chromium alloys at elevated temperatures. The diagram indicates the approximate effect of carbon in extending the austenite region into the richer chromium alloys. This diagram may assist in correlating the apparently conflicting results of various observers. Data by Ruf[5] and Kinzel[6] indicate that the austenite region extends to about 12 per cent chromium for iron-chromium alloys containing negligible amounts of carbon. Matsushita[7] found critical regions on iron-chromium alloys containing from 0 to 20 per cent chromium and 0.6 per cent carbon. The present investigation clearly shows that an iron-chromium alloy containing 24.6 per cent chromium and 0.74 per cent carbon undergoes a transformation from the alpha to the gamma phase and that alloys containing about 17 per cent chromium and about 0.05 per cent carbon have slight critical regions. It therefore appears from the results of all of these investigations that for iron-

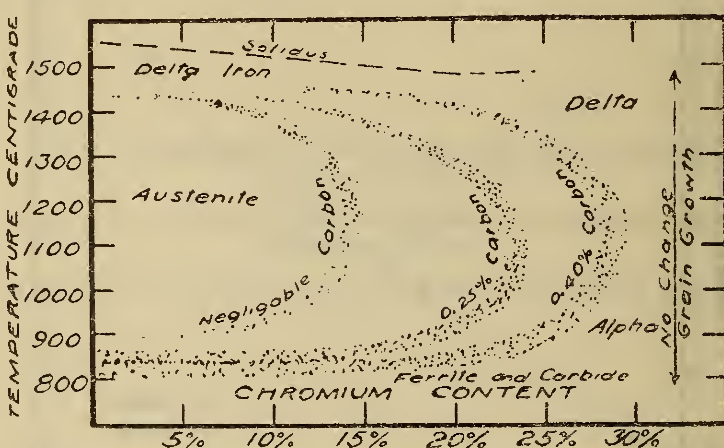



FIGURE 10.—*Approximate effect of carbon on the austenite region in iron-chromium alloys* (*Bain*)

chromium alloys containing negligible carbon the austenite region extends from 0 to about 12 per cent chromium, for alloys containing about 0.05 per cent carbon the region extends from 0 to at least 17 per cent chromium, and for alloys containing larger contents of carbon the austenite region is extended to higher chromium contents.

The average coefficients of expansion given in Table 5 were derived from the expansion curves of Figures 5 to 9, inclusive. The table shows that the coefficients of expansion increase gradually with temperature. The coefficients of expansion indicate a tendency to decrease slightly with increase in the chromium content of the iron-chromium alloys containing from 17.0 to 24.6 per cent chromium.

Table 6 gives a summary of the coefficients of expansion obtained by various observers, including the values obtained by the present author. These coefficients of expansion refer to various iron-chromium alloys containing from 0 to 60 per cent chromium and from 0 to 6.7 per cent carbon. The treatments (cast, annealed, quenched, etc.) are indicated in the table.

[5] K. Ruf, Zeitschrift für Elektrochemie, vol. 34, p. 813; 1928.
[6] A. B. Kinzel, Heat Treating and Forging, vol. 14, p. 372; 1928.
[7] T. Matsushita, Science Reports Tôhoku Imperial University (first series), vol. 9, p. 243; 1920.

TABLE 5.—*Average coefficients of expansion of iron-chromium alloys*

| Sample | Chemical composition | | Heat treatment | Average coefficients of expansion per degree centigrade | | | | | | | | | | Change in length due to heat treatment received during test |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Chromium | Carbon | | 20° to 60° C. | 20° to 100° C. | 20° to 200° C. | 20° to 300° C. | 20° to 400° C. | 20° to 500° C. | 20° to 600° C. | 20° to 700° C. | 20° to 800° C. | 20° to 900° C. | |
| | *Per cent* | *Per cent* | | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | *Per cent* |
| 1299 | 17.0 | 0.04 | Hot-rolled | 10.3 | 10.6 | 10.8 | 11.1 | 11.4 | 11.7 | 11.9 | 12.1 | 12.5 | 13.1 | ------- |
| 1300 [1] | 17.1 | .06 | Annealed | 10.2 | 10.3 | 10.7 | 11.0 | 11.2 | 11.4 | 11.7 | 11.9 | 12.4 | 12.9 | −0.01 |
| 1300A [2] | 17.1 | .06 | do | 10.2 | 10.3 | 10.5 | 10.9 | 11.1 | 11.3 | 11.5 | 11.8 | 12.3 | 12.9 | +.00 |
| 1427 [3] | 17.6 | .04 | do | 9.7 | 10.1 | 10.4 | 10.7 | 11.1 | ------ | 11.6 | 11.8 | 12.2 | 12.8 | ------- |
| 1428 [4] | 24.6 | .74 | do | 10.5 | 10.2 | 10.5 | 10.7 | 11.0 | ------ | 11.4 | 11.6 | 12.0 | 12.5 | ------- |
| 1294 | 24.6 | .16 | Hot-rolled | 10.3 | 10.0 | 10.3 | 10.6 | 10.9 | 11.2 | 11.3 | 11.6 | 12.2 | 12.7 | ------- |

[1] Coefficients of expansion obtained on second test; coefficient of expansion between 925° and 1,000°C. is $19.0\times10^{-6}$. On first test, the average coefficient of expansion is $10.9\times10^{-6}$ between 100° and 200° C. and $11.6\times10^{-6}$ between 200° and 300° C.; on cooling, the average coefficient of contraction is $10.9\times10^{-6}$ between 300 and 20° C.

[2] Coefficient of expansion between 925° and 1,000° C. is $18.2\times10^{-6}$.

[3] Coefficient of expansion between 925° and 1,000° C. is $17.9\times10^{-6}$.

[4] Coefficient of expansion between 20° and 950° C. is $12.8\times10^{-6}$.

TABLE 6.—*Summary of coefficients of expansion of iron-chromium alloys*

| Sample | Chemical composition: Chromium | Chemical composition: Carbon | Treatment | Average coefficients of expansion per degree centigrade: Room temperature to 100° C. | Room temperature to 200° C. | 0° to 250° C. | Room temperature to 300° C. | Room temperature to 400° C. | Room temperature to 500° C. | Room temperature to 600° C. | Room temperature to 700° C. | Room temperature to 800° C. | Room temperature to 900° C. | Room temperature to 1,000° C. | Observer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Per cent* | *Per cent* | | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | |
| S507 | 0.0 | 0.02 | Annealed | 12.0 | | | 13.3 | | | 14.7 | | | | | Souder and Hidnert.[1] |
| | 0 | ([2]) | Cast | | | [3] 12.6 | | | | | | | | | Ruf.[4] |
| 2811F [5] | 0 | <.1 | do | 13.3 | | | | | | | | | | 17.8 | Dean.[6] |
| S482 | 0.19 | 1.28 | Annealed | 11.0 | | | 12.0 | | | 14.1 | | | | | Souder and Hidnert.[1] |
| S552 | .57 | .36 | do | 11.8 | [7] 12.3 | | 13.1 | [7] 13.6 | [7] 14.1 | 14.5 | [7] 14.9 | | | | Do.[1] |
| 1,223 | .78 | .40 | Quenched and drawn | 12.8 | [7] 13.4 | | | | | | | | | | Hidnert.[8] |
| S560 | .82 | .34 | Annealed | 11.6 | [7] 12.1 | | 12.9 | [7] 13.7 | [7] 14.2 | 14.6 | [7] 14.9 | | | | Souder and Hidnert.[1] |
| S558 | .85 | .12 | do | 11.6 | [7] 12.1 | | 12.7 | [7] 13.2 | [7] 13.6 | 14.0 | [7] 14.3 | | | | Do.[1] |
| S557 | .92 | .17 | do | 11.3 | [7] 11.6 | | 12.5 | [7] 13.2 | [7] 13.7 | 14.2 | [7] 14.5 | | | | Do.[1] |
| 1,048 | .96 | .34 | Quenched and drawn | 11.8 | [7] 12.7 | | | | | | | | | | Hidnert.[8] |
| S546 | 1.00 | .35 | Annealed | 12.4 | [7] 12.6 | | 13.3 | [7] 13.8 | [7] 14.2 | 14.5 | [7] 14.7 | | | | Souder and Hidnert.[1] |
| S555 | 1.15 | .14 | do | 11.2 | [7] 12.0 | | 12.7 | [7] 13.5 | [7] 13.9 | 14.3 | [7] 14.6 | | | | Do.[1] |
| S551 | 1.17 | .35 | do | 11.0 | [7] 11.8 | | 12.9 | [7] 13.6 | [7] 14.1 | 14.5 | [7] 14.7 | | | | Do.[1] |
| 257 | 1.20 | .40 | Quenched and drawn | 11.6 | [7] 12.4 | | | | | | | | | | Hidnert.[8] |
| 5 [5] | 3.12 | 2.66 | Cast | 10.2 | 10.6 | | 11.6 | 12.4 | 13.2 | 13.7 | 14.0 | | | | Baraduc-Muller.[9] |
| | | | Quenched | 9.5 | 9.1 | | 10.7 | 13.4 | | | | | | | |
| | 6 | ([2]) | Cast | | | [3] 11.3 | | | | | | | | | Ruf.[4] |
| 6 [10] | 7.40 | 1.62 | do | 10.9 | 10.7 | | 11.2 | 12.1 | 12.9 | 13.8 | 15.7 | 14.7 | 15.0 | | Baraduc-Muller.[9] |
| | | | Quenched | 9.4 | 9.9 | | 10.5 | 10.8 | 11.3 | 11.6 | 12.1 | 12.9 | 14.5 | 16.8 | |
| 1,218 | 11.9 | .09 | Annealed | 10.6 | 10.6 | | 11.0 | 11.4 | 11.7 | | | | | | Hidnert and Sweeney.[11] |
| | 12 | ([2]) | Cast | | | [3] 10.7 | | | | | | | | | Ruf.[4] |
| 1,195 | 12.0 | .09 | Annealed | | 10.2 | | | 11.2 | | 12.0 | | | | | Hidnert and Sweeney.[11] |
| 1,218A | 12.2 | .09 | do | 9.8 | 10.4 | | 10.8 | 11.2 | 11.6 | 11.9 | | 12.3 | | | Do.[11] |
| 1,219 | 12.2 | .09 | do | 10.2 | 10.4 | | 10.8 | 11.2 | 11.7 | | | | | | Do.[11] |
| 1,219A | 12.4 | .09 | do | 9.5 | 10.3 | | 10.7 | 11.2 | 11.6 | 12.1 | | | | | Do.[11] |
| | 13 | .3 | Wrought | | 10.9 | | | | | | | | | | ([12]). |
| S565 | 13.00 | .30-.40 | Annealed | 10.0 | [7] 10.4 | | 11.0 | [7] 11.4 | [7] 11.8 | 12.2 | [7] 12.4 | | | | Souder and Hidnert.[1] |
| S620 | 13.10 | .30 | do | 10.3 | 10.7 | | [7] 11.3 | [7] 11.5 | [7] 11.8 | 12.1 | [7] 12.4 | [7] 12.5 | | | Do.[13] |
| S680 [14] | 13.10 | .30 | Hardened | 9.6 | | | | | | | | | | | Do.[13] |
| | | | | 9.9 | 9.8 | | | [7] 9.8 | [7] 10.6 | 11.2 | | [7] 11.8 | | | |
| 1,117 [15] | 13.5 | .13 | Annealed | | 10.4 | | | 11.3 | | 12.1 | | 12.8 | | | Hidnert and Sweeney.[11] |
| | | | | 10.2 | 10.5 | | 10.9 | 11.3 | 11.7 | 12.1 | | 12.6 | | | |
| 1,156 [15] | 15.9 | .12 | do | | | | | 10.7 | | 11.2 | | | | | Do.[11] |
| | | | | | | | 10.8 | | | 11.8 | | | | | |
| 1,157 | 16.4 | .13 | Quenched and drawn | | | | 11.7 | | | 11.8 | | | | | Do.[11] |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1,157A | 16.4 | .13 | do | 9.9 | 10.1 | | 10.4 | 10.9 | 11.3 | 11.6 | | 12.4 | | | Do.[11] |
| 1,299 | 17.04 | .04 | Hot-rolled | 10.6 | 10.8 | | 11.1 | 11.4 | 11.7 | 11.9 | 12.1 | 12.5 | 13.1 | | Hidnert.[16] |
| 1,300 | 17.08 | .06 | Annealed | 10.3 | 10.7 | | 11.0 | 11.2 | 11.4 | 11.7 | 11.9 | 12.4 | 12.9 | | Do.[16] |
| 1,300A | 17.08 | .06 | do | 10.3 | 10.5 | | 10.9 | 11.1 | 11.3 | 11.5 | 11.8 | 12.3 | 12.9 | | Do.[16] |
| 1,427 | 17.6 | .04 | do | 10.1 | 10.4 | | 10.7 | 11.1 | | 11.6 | 11.8 | 12.2 | 12.8 | | Do.[16] |
| | 18 | (2) | Cast | | | [3] 10.3 | | | | | | | | | Ruf.[4] |
| | 20 | | Wrought and cast | | | | | | | | | [17] 11.9 | | | (12). |
| 2,846F [5] | 20 | <.1 | Cast | 10.7 | | | | | | | | | | 12.3 | Dean.[6] |
| | 20 | .3 | Wrought | | | [18] 9.9 | | | [19] 10.2 | | [19] 10.3 | | | | (12). |
| 1,428 | 24.6 | .74 | Annealed | 10.2 | 10.5 | | 10.7 | 11.0 | | 11.4 | 11.6 | 12.0 | 12.5 | | Hidnert.[16] |
| 1,294 | 24.63 | .16 | Hot-rolled | 10.0 | 10.3 | | 10.6 | 10.9 | 11.2 | 11.3 | 11.6 | 12.2 | 12.7 | | Do.[16] |
| | 25 | (2) | Cast | | | [3] 10.0 | | | | | | | | | Ruf.[4] |
| | 25 | | do | | | | | | | | | [17] 15.3 | | | (12). |
| CN21-7 | 26.5 | .38 | Normalized | | 10.3 | | | 11.0 | | 11.4 | | | | | Hidnert and Sweeney.[20] |
| CN21-7 | 26.5 | .38 | Quenched | | 11.7 | | | 12.4 | | 12.2 | | | | | Do.[20] |
| | 32 | (2) | Cast | | | [3] 9.7 | | | | | | | | | Ruf.[4] |
| 2850F [5] | 40 | <.1 | do | 9.8 | | | | | | | | | | 13.7 | Dean.[6] |
| 3 [21] | 45.9 | 6.67 | do | 7.5 | 7.7 | | 7.7 | 8.4 | 8.7 | 9.1 | 9.5 | 9.8 | 10.0 | 10.2 | Baraduc-Muller.[9] |
| | | | Quenched | 9.3 | 8.5 | | 8.6 | 8.9 | 9.0 | 9.2 | 9.4 | 9.5 | 9.5 | 9.4 | |
| 2 [21] | 47.60 | 2.84 | Cast | 8.0 | 8.3 | | 8.3 | 8.8 | 9.3 | 9.8 | 10.2 | 10.6 | 10.8 | 10.9 | Do.[9] |
| | | | Quenched | 9.2 | 8.9 | | 9.0 | 9.2 | 9.8 | 10.0 | 10.5 | 10.8 | 10.8 | 10.9 | |
| | 50 | (2) | Cast | | | [3] 9.3 | | | | | | | | | Ruf.[4] |
| 4 [21] | 53.3 | 6.21 | do | 7.5 | 7.0 | | 7.1 | 7.4 | 7.8 | 8.3 | 8.7 | 9.0 | 9.2 | 9.3 | Baraduc-Muller.[9] |
| | | | Quenched | 7.2 | 6.7 | | 6.8 | 7.2 | 7.6 | 7.9 | 7.9 | 8.2 | 8.3 | 8.4 | |
| 2851F [5] | 60 | <.1 | Cast | 9.0 | | | | | | | | | | 13.9 | Dean.[6] |

[1] B. S. Sci. Paper No. 433; 1922.
[2] Carbon-free.
[3] Obtained from Ruf's curve.
[4] Zeitschrift für Elektrochemie, vol. 34, p. 813; 1928.
[5] All coefficients of expansion except those for the range from room temperature to 100° C. were computed in 1931 from the published data of the observer.
[6] Rensselaer Polytechnic Institute, Engineering and Science Series, No. 26; 1930.
[7] Derived in 1931 from unpublished original data of observers.
[8] Data reported by Mathews, Transactions of the American Institute of Mining and Metallurgical Engineers, vol. 67, p. 133; 1922.
[9] Revue de Métallurgie, vol. 7, p. 657; 1910.
[10] All coefficients of expansion except those for the ranges from room temperature to 100° C. and from room temperature to 900° C. were derived in 1931 from the published data of the observer.
[11] B. S. Sci. Paper No. 570; 1928.
[12] Data furnished by manufacturer of alloy (Proceedings American Society for Testing Materials, vol. 24, p. 189; 1924).
[13] B. S. Sci. Paper No. 426; 1921.
[14] All coefficients of expansion were obtained on second heating except $9.6 \times 10^{-6}$ (obtained on first heating).
[15] Coefficients on first line were obtained on first heating and those on second line were obtained on second heating.
[16] Present investigation.
[17] From 0° to 800° C.
[18] From 23° to 250° C.
[19] Computed from coefficients given in publication cited in footnote 12.
[20] Data reported by Mathews, Transactions of the American Institute of Mining and Metallurgical Engineers, vol. 71, p. 568; 1925.
[21] All coefficients of expansion except those for the ranges from room temperature to 100° C. and from room temperature to 1,000° C. were derived in 1931 from the published data of the observer.

Figure 11 indicates the effects of chromium content, carbon content, heat treatment, etc., on the coefficients of expansion of iron-chromium alloys for various temperature ranges. The data were taken from Table 6. The results plotted in the figure indicate the observers, the ranges of carbon contents of the alloys and their heat treatments. All coefficients of expansion represent values for annealed [8] alloys except those indicated otherwise. The curves of the coefficients of expansion of annealed iron-chromium alloys are summarized in Figure 12 and indicate that the coefficients of expansion increase with temperature and generally decrease with increase in chromium content. For alloys containing from about 12 to 25 per cent chromium, the changes in the coefficients of expansion are small.

### 3. NICKEL-CHROMIUM-IRON ALLOYS

This subsection gives the results obtained on 26 samples of nickel-chromium-iron alloys containing from 1.3 to 70.1 per cent nickel, 4.9 to 26.7 per cent chromium and 6.6 to 74.7 per cent iron. The chemical composition, heat treatment and other information about the samples have been given in Table 1.

The expansion observations [9] obtained on the nickel-chromium-iron alloys are shown in subsequent figures. Some of the expansion curves show critical regions. A consideration of the nature of nickel-chromium-iron alloys may furnish information relating to the causes of these critical regions.

Bain and Griffiths [10] state "Obviously, no two metals could develop a single homogeneous series of solid solutions unless they were of the same identical type. Thus we can conceive of a continuous series of solid-solution alloys from pure alpha (or delta) iron to pure chromium or from pure gamma iron to pure nickel, and this is precisely what exists. Hence, first of all the ternary diagram is certain to contain two solid solutions—one embracing gamma iron and nickel with some chromium in solution and the other embracing alpha (or delta) iron and chromium and containing some nickel. There will be the two-phase zone between these single solutions types."

Pomey and Voulet [11] published a ternary diagram [12] of nickel-chromium-iron alloys in conjunction with the equilibrium diagrams of nickel-chromium, iron-chromium, and iron-nickel alloys. Figure 13 shows the ternary diagram and the equilibrium diagrams mentioned. (The ternary diagram has been reproduced on an enlarged scale.) Pomey and Voulet divided the ternary diagram representing the nickel-chromium-iron system into nine regions as follows:

---

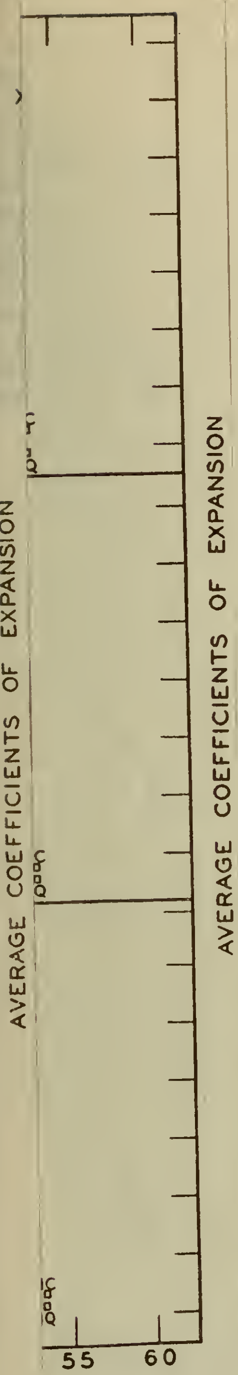
[8] The curves indicated in the figure were obtained from the coefficients of expansion of annealed alloys investigated at the National Bureau of Standards by Souder, Hidnert, and Sweeney between 1921 and 1931, inclusive. The dotted portions of the curves indicate that sufficient data have not been obtained in the region of low chromium content.

[9] Portions of some expansion curves are indicated by dotted lines in order to show that sufficient observations have not been obtained. Some duplicate samples (marked A) were investigated in order to obtain additional data.

[10] E. C. Bain and W. E. Griffiths, Transactions American Institute of Mining and Metallurgical Engineers, vol. 75, p. 166; 1927.

[11] J. Pomey and P. Voulet, Chimie & Industrie (special number), February, 1929, p. 404.

[12] After the present manuscript was completed, the author's attention was called to a recent preliminary ternary diagram by R. H. Aborn and E. C. Bain (Transactions American Society for Steel Treating, vol. 18, p. 837; 1930). They state that the greatest usefulness of the ternary diagram is in indicating the trends which may be expected in individual compositions, and for this purpose the highest accuracy is not required.. The construction of the ternary system, in accordance with the phase rule and the binary systems, was also recently derived by F. Wever and W. Jellinghaus (Mitt. Kaiser-Wilhelm-Inst. Eisenforsch. Düsseldorf, vol. 13, p. 93; 1931) and the boundaries of the space sections were determined approximately by thermic, dilatometric, metallographic and X-ray investigations.




*observers.* (*Cur*

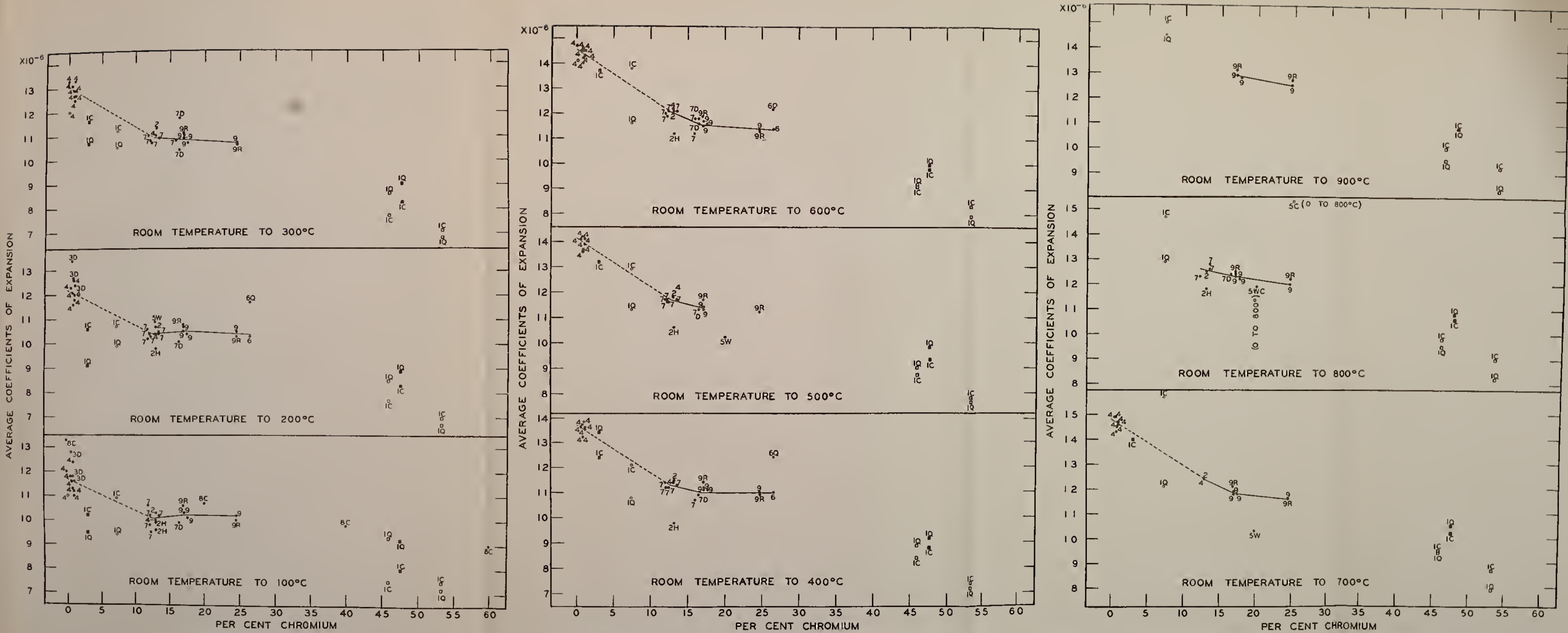



FIGURE 11.—*Effects of chromium content, carbon content, and heat treatment on the coefficients of expansion of iron-chromium alloys investigated by various observers. (Curves represent data on annealed alloys investigated at Bureau of Standards)*

The following symbols were used:

| | Observer | Date |
|---|---|---|
| 1. | Baraduc-Muller | 1910 |
| 2. | Souder and Hidnert | 1921 |
| 3. | Hidnert | 1922 |
| 4. | Souder and Hidnert | 1922 |
| 5. | ? | 1924 |
| 6. | Hidnert and Sweeney | 1925 |
| 7. | Hidnert and Sweeney | 1928 |
| 8. | Dean | 1930 |
| 9. | Hidnert | 1931 |

C = Cast.
D = Quenched and drawn.
H = Hardened.
Q = Quenched.
R = Hot-rolled.
W = Wrought.

NOTE.—Every point not marked with a letter represents an annealed alloy.
● = 0 to 1 per cent carbon.
○ = 1 to 2 per cent carbon.
■ = 2 to 3 per cent carbon.
□ = 6 to 7 per cent carbon.

*Region 1.*—Solid solution alpha (ferrite), stable at all temperatures, isomorphous with alpha iron and chromium.

*Region 2.*—Alpha phase (ferrite or martensite) transformable entirely into austenite by heating above $A_3$ (pearlitic and martensitic steels).

*Region 3.*—Alpha phase (ferrite or martensite) transformable entirely into austenite by heating above $A_3$ and at least partially into delta iron by heating above $A_4$ (pearlitic and martensitic steels).

*Region 4.*—Alpha phase partially transformable into austenite by heating to a high temperature.

*Region 5.*—Solid solution gamma stable at all temperatures (reversible nickel-iron-chromium alloys), isomorphous with pure nickel.

*Region 6.*—Gamma phase metastable at ordinary temperature, transformable into alpha phase by cold work or by cooling to a very low temperature (irreversible iron-nickel-chromium alloys).

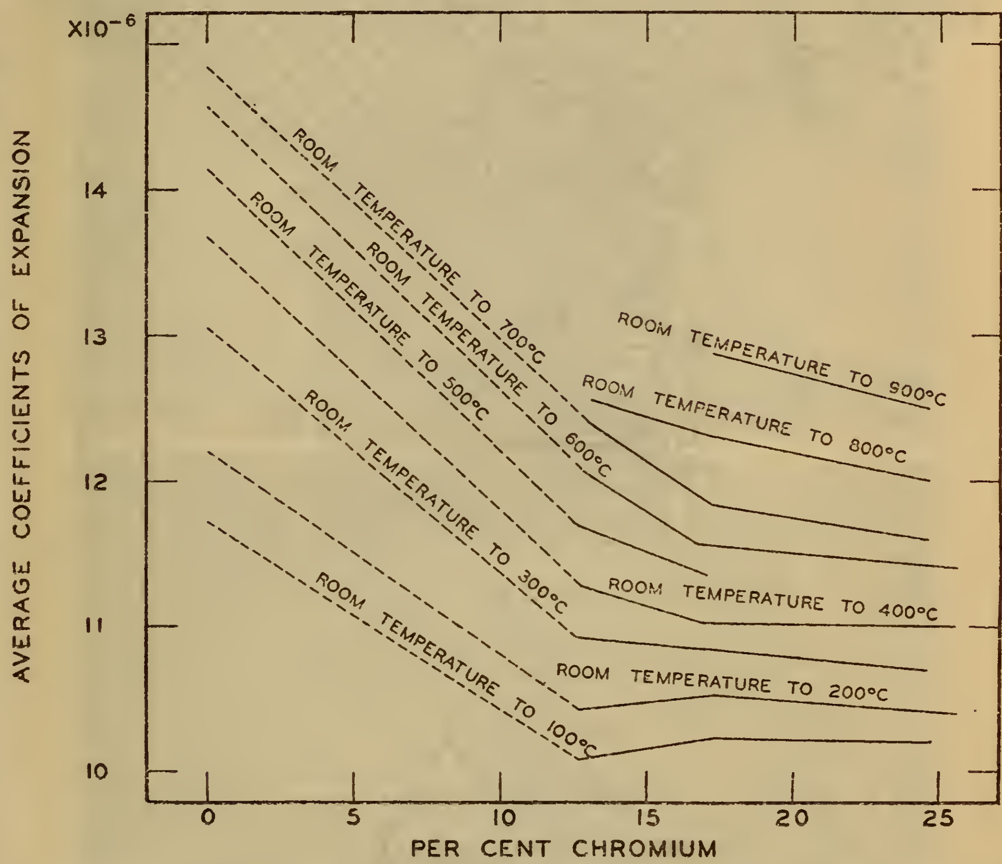



FIGURE 12.—*Relations between the chromium content and the coefficients of expansion of annealed iron-chromium alloys*

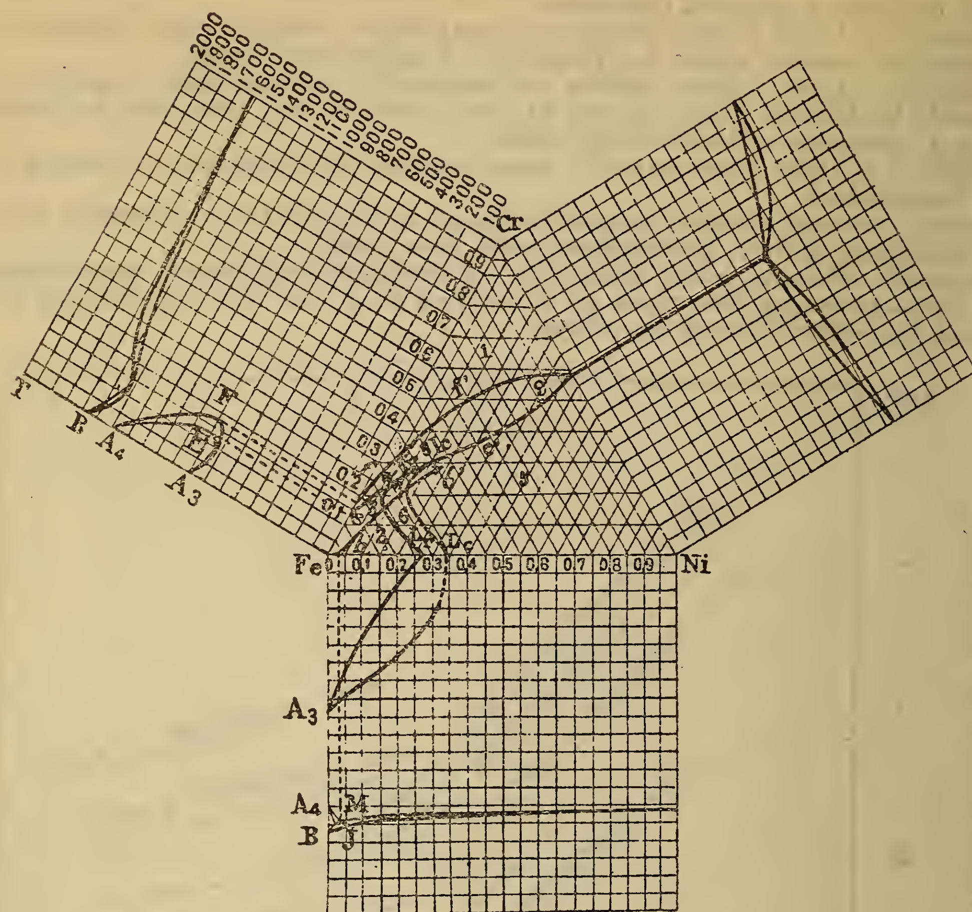
*Region 7.*—Gamma phase metastable like the preceding, but in addition to this can be transformed into delta phase by heating to a very high temperature.

*Region 8.*—Mixture of metastable alpha and gamma phases, the proportion varying with the temperature of the tempering.

*Region 9.*—Mixture of two phases 1 and 5, respectively, isomorphous with chromium and nickel.

The nickel-chromium-iron alloys used in the present investigation may be classified in accordance with the regions indicated in the ternary diagram which is based on binary diagrams of the nickel-chromium, iron-chromium, and nickel-iron systems containing little or no carbon. The regions in which the alloys have been placed, will be indicated in the following paragraphs.

*Region 1.*—Figure 14 shows expansion data on two samples (1,314 and 1,314A) of cast nickel-chromium-iron alloy (Ni 1.3, Cr 26.7,



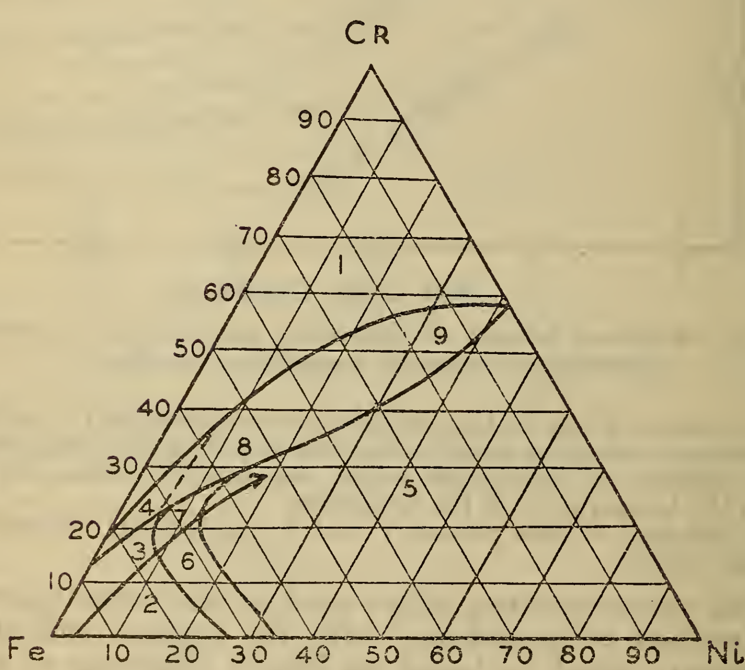


FIGURE 13.—*Ternary diagram of nickel-chromium-iron alloys and equilibrium diagrams of nickel-chromium, iron-chromium, and iron-nickel alloys (Pomey and Voulet)*

An enlarged view of the ternary diagram is shown in the lower part of the figure.


FIGURE 15.—*Microstructure of nickel-chromium-iron alloy (1314A).* $\times$ *500*

Ni 1.3, Cr 26.7, Fe 70.0, C 0.72, Mn 0.57, Si 0.66 per cent. *a*, As cast; *b*, after second expansion test.

C 0.72 per cent). The expansion curve for the first heating on each sample shows a rapid increase in expansion between 700° and 800° C.

Figure 15 shows two micrographs [13] of sample 1314A as cast and after the second expansion test. These micrographs indicate that the heat treatment incident to the expansion determinations caused a precipitation of carbide particles from the solid solution alpha (ferrite). It appears that the precipitation of carbide caused the rapid increase in expansion [14] between 700° and 800° C.

In the second expansion test of sample 1314A, the expansion curve does not show a rapid increase in expansion. The alloy therefore

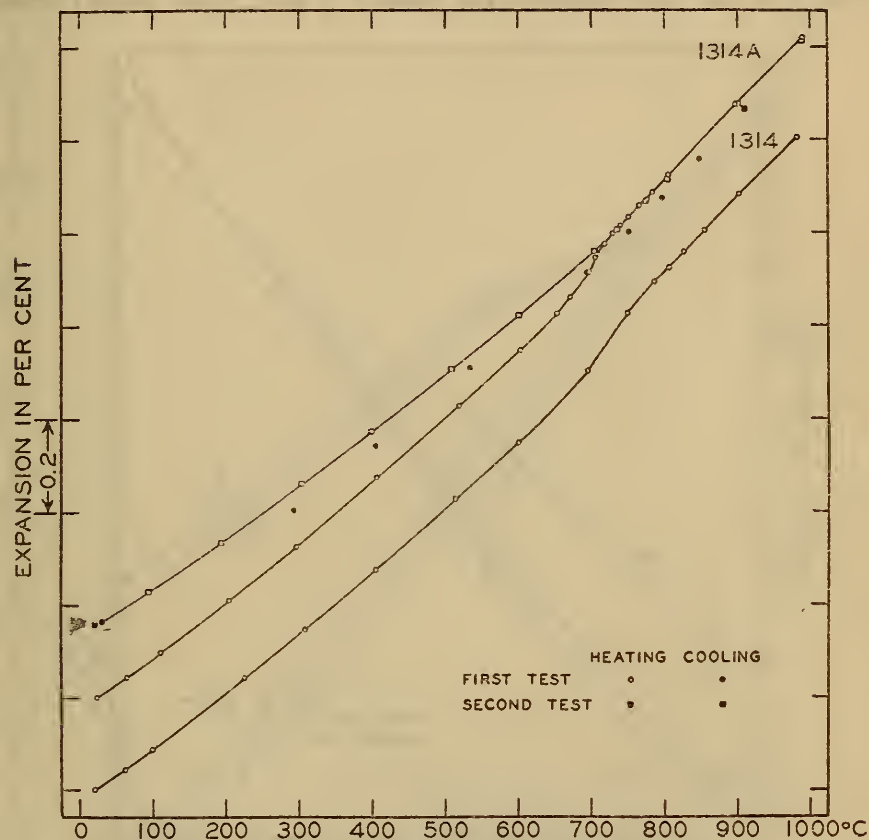



FIGURE 14.—*Linear thermal expansion of two samples of cast nickel-chromium-iron alloy*

Ni 1.3, Cr 26.7, Fe 70.0, C 0.72, Mn 0.57, Si 0.66 per cent.

appears to be stable (between 20° and 1,000° C.) after the precipitation of carbide in the first expansion test.

*Region 3.*—Figures 16 and 17 show the expansion observations obtained on two samples (1411 and 1411A) of hot-rolled nickel-chromium-iron alloy (Ni 7.5, Cr 14.0, C 0.30 per cent) containing appreciable amounts of silicon and tungsten. The expansion curve on the first heating in each hot-rolled sample (austenitic) does not indicate a transformation, but on cooling from about 200° C. to room tempera-

[13] Microscopic examination of sample 1314A and other samples in this paper was made by E. C. Groesbeck and H. O. Willier, of the National Bureau of Standards. Small pieces for microscopic examination were cut transversely from the rods used in the thermal expansion investigation. The etching reagent was a mixture of 2 parts concentrated hydrochloric acid, 1 part concentrated nitric acid, and 3 parts glycerine (by volume) The magnification for all the micrographs was 500 diameters.

[14] It is possible to classify samples 1314 and 1314A in region 4, for they are near the border between regions 1 and 4. The rapid increase in expansion between 700° and 800° C. may then be assumed to be due to the partial transformation from one phase to another.

ture there is a marked expansion due to a transformation from austenite to the alpha phase (ferrite or martensite). In the second heating above 600° C. there is a transformation from the alpha phase to austenite. In the second cooling (1411A) the curve nearly coincides with the curve obtained in the first cooling, and also indicates the transformation from austenite to alpha phase. The expansion curve on the third heating (1411A) is similar to the curve on the second heating.

Two nickel-chromium-iron alloys investigated by Andrew, Rippon, Miller, and Wragg [15] and two alloys by Souder and Hidnert [16] contain from 0.5 to 3.9 per cent nickel and from 0.5 to 2.5 per cent chromium.

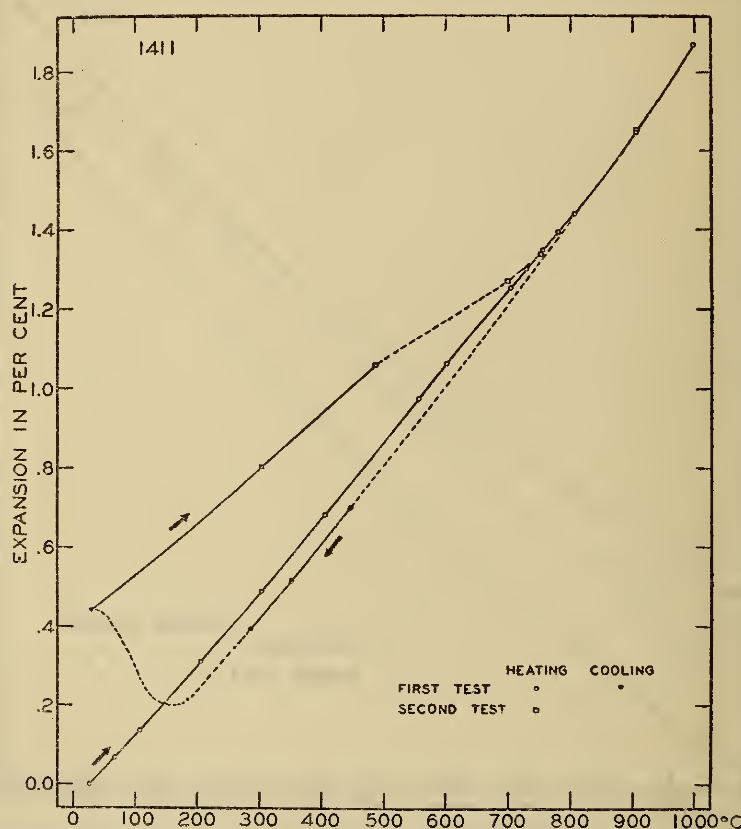



FIGURE 16.—*Linear thermal expansion of hot-rolled nickel-chromium-iron alloy*

Ni 7.5, Cr 14.0, Fe 74.7, C 0.30, Mn 0.17, Si 2.40, P 0.014, S 0.012, W 0.89 per cent.

These alloys may also be classified in region 3. The expansion curves indicate transformations in these alloys.

*Region 5.*—All of the cast nickel-chromium-iron alloys investigated, except samples 1314, 1314A, 1296, 1296A, and 1303, may be placed in region 5 of the ternary diagram. (Fig. 13.) The alloys in this region form solid solutions of gamma iron and chromium in nickel. Bain and Griffiths [17] state that these compositions are without transformation and that a very long annealing treatment causes some precipitation of excess carbide in parallel planes within the grains.

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[15] J. H. Andrew, J. E. Rippon, C. P. Miller, and A. Wragg, Journal Iron and Steel Institute, vol. 101, p. 527; 1920.

[16] W. Souder and P. Hidnert, B. S. Sci. Paper No. 433; 1922.

[17] See footnote 10, p. 1044.

Figures 18 to 23, inclusive, show the expansion data obtained on the 10 cast nickel-chromium-iron samples (1306, 1306A, 1295, 1304, 1291, 1302, 1298, 1305, 1301, and 1313) grouped in region 5. Nearly all of the samples contain appreciable amounts of manganese and silicon. The expansion curve for the first heating (to about 1,000° C.) on each sample except samples 1298 [18] and 1313, [19] shows a retardation or decrease in expansion between 700° and 800° C. The contraction

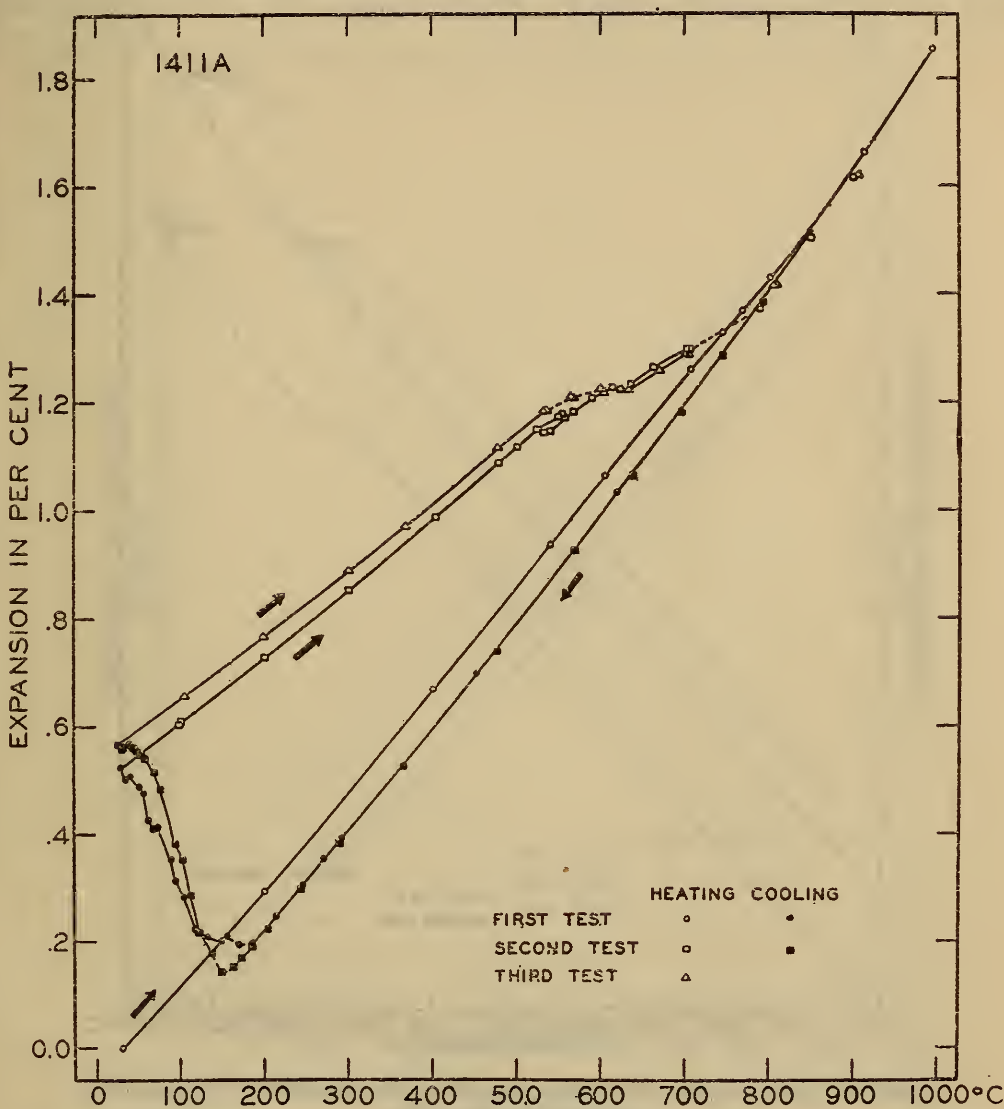


FIGURE 17.—*Linear thermal expansion of hot-rolled nickel-chromium-iron alloy*

Ni 7.5, Cr 14.0, Fe 74.7, C 0.30, Mn 0.17, Si 2.40, P 0.014, S 0.012, W 0.89 per cent.

or retardation in expansion generally appears to decrease with increase in nickel content. The curves on cooling do not show critical regions.

Figures 24 to 27, inclusive, show micrographs obtained on four of the cast alloys (1295, 1302, 1298, and 1313) before and after expansion tests. These micrographs indicate that the heating during the expansion tests caused precipitation of excess carbide from solid solution gamma (austenite). The appreciable contraction on heating, with a

[18] Before observation 11 (fig. 22) sample was heated to about 800° C. when heating current was broken for one and one-fourth hours; sample cooled to about 600° C. (observation 11).

[19] Contains largest contents of manganese and silicon.

resultant decrease in expansion, noted for samples 1295 and 1302 appears to be connected with the precipitation of the carbide particles.

The expansion curves obtained on the second or third heating (to 1,000° C.) of the cast alloys do not show retardation or decrease in expansion. The curves on heating and cooling are nearly reversible between room temperature and 1,000° C. The alloys therefore appear to be stable after the precipitation of excess carbide in the

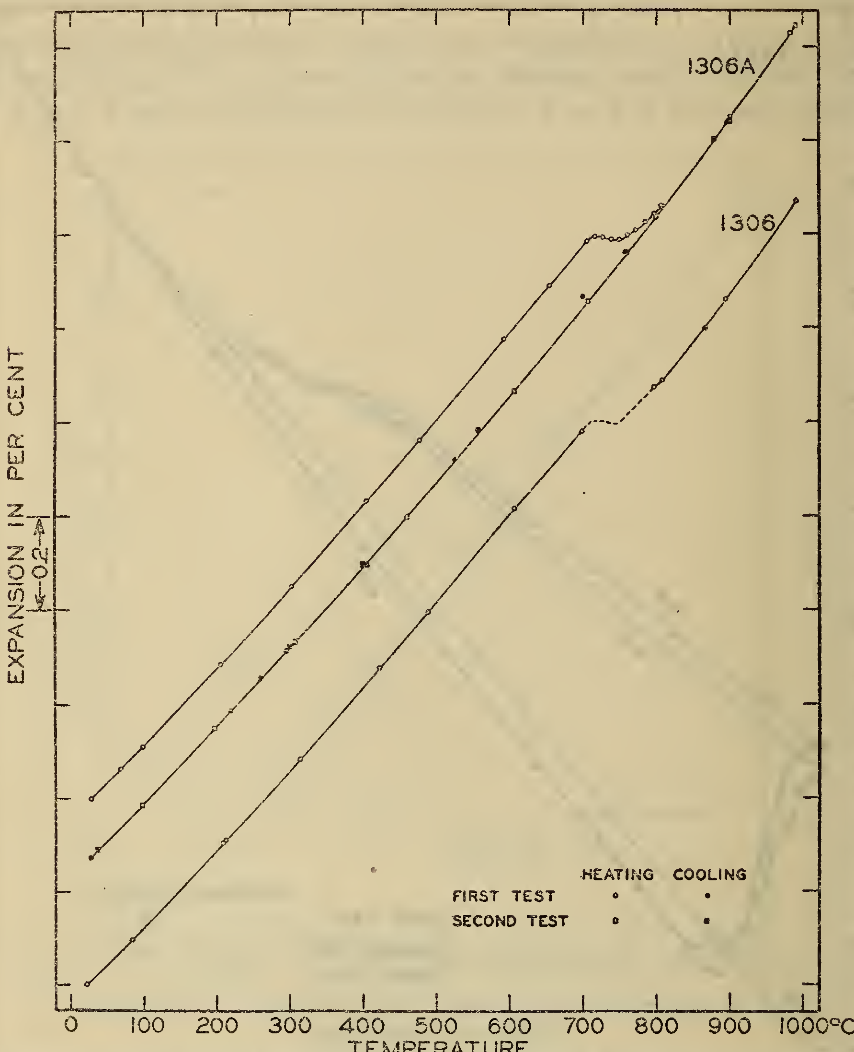


FIGURE 18.—*Linear thermal expansion of two samples of cast nickel-chromium-iron alloy*

Ni 19.55, Cr 19.55, Fe 58.93, C 1.25, Mn 0.15, Si 0.09, Cu 0.48 per cent.

first heating. The precipitation of carbide was probably complete during the first heating.

Before the third expansion tests were made on samples 1295 and 1302 (figs. 19 and 21), they were heated from room temperature to 900° C. in hydrogen and cooled to room temperature in hydrogen. No effect due to hydrogen[20] was observed on the expansion curves obtained in the third tests.

[20] H. S. Rawdon, P. Hidnert, and W. A. Tucker, Transactions American Society for Steel Treating, vol. 10, p. 233; 1926.

Figure 28 shows reversible expansion curves of two hot-rolled alloys (1404 and 1403) that are austenitic and stable (between room temperature and 1,000° C.).

*Region 6.*[21]—Figure 29 shows the expansion data obtained on a cast alloy (1303). The curve obtained on heating in the second [22] expansion test shows a retardation in expansion between 700° and 800° C. This retardation in expansion was apparently caused by the precipitation of excess carbide which is indicated by the micro-

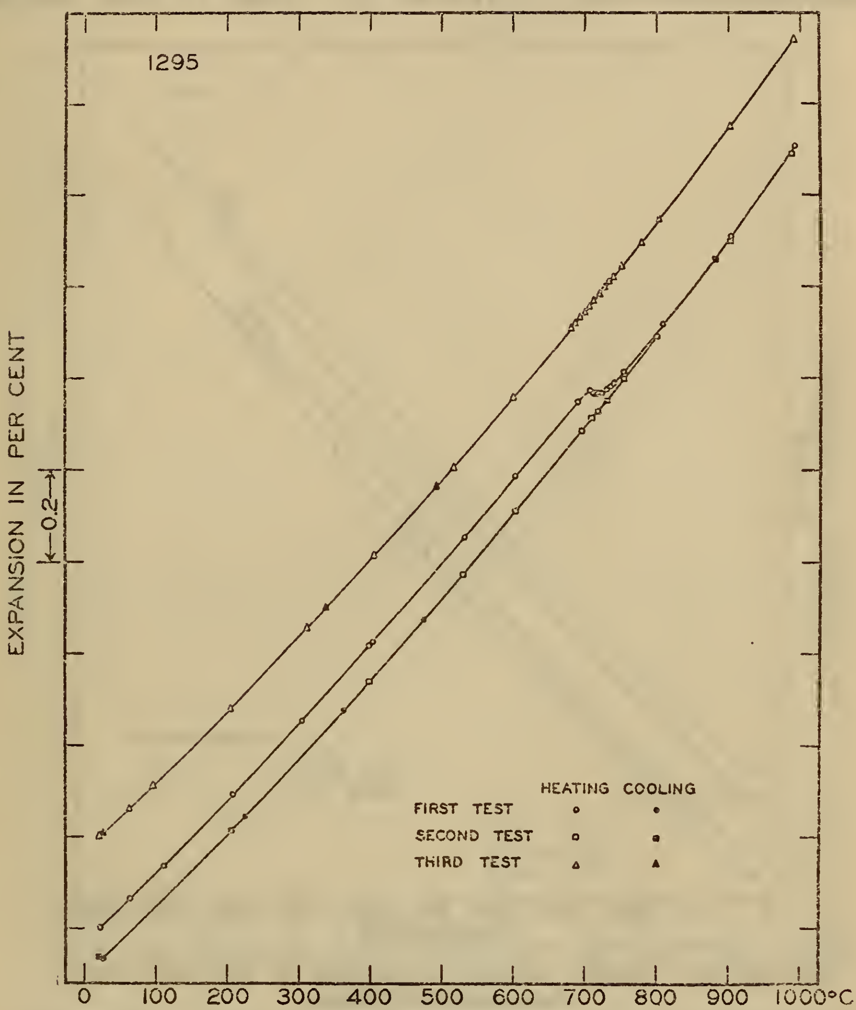


FIGURE 19.—*Linear thermal expansion of cast nickel-chromium-iron alloy*

Ni 27.78, Cr 18.50, Fe 50.30, C 0.58, Mn 0.83, Si 1.90, Al 0.08 per cent.

graphs [23] in Figure 30. The carbide was precipitated from the solid solution gamma (austenite), as was found in cast alloys of region 5.

The curves obtained in the third and fourth [24] expansion tests on sample 1303 do not show retardations in expansion. After the precipitation of carbide in the second expansion test the sample appeared to be stable between 20° and 1,000° C.

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[21] Data on a loys near the border between regions 6 and 7 will be discussed later.
[22] First test only to about 300° C.
[23] It is interesting to note that the micrograph of the heat-treated sample shows that the carbide particles are concentrated along the network of the dendritic structure.
[24] Before the fourth expansion test, the sample was heated and cooled in hydrogen, in a similar manner as was done with samples 1295 and 1302 (region 5).

Figure 31 shows the expansion curve of a forged and annealed austenitic nickel-chromium-iron alloy (1310). This curve does not indicate any transformation between room temperature and 1,000° C. Data on the thermal expansion of similar alloys at low temperatures are necessary in order to confirm Pomey and Voulet's statement relating to the transformation from gamma phase to alpha phase.

*Region 7.* [25]—Figures 32 to 34, inclusive, show the results obtained on the thermal expansion of two cast samples (1296 and 1296A) of nickel-chromium-iron alloy (Ni 8.41, Cr 21.66, C 1.15) containing

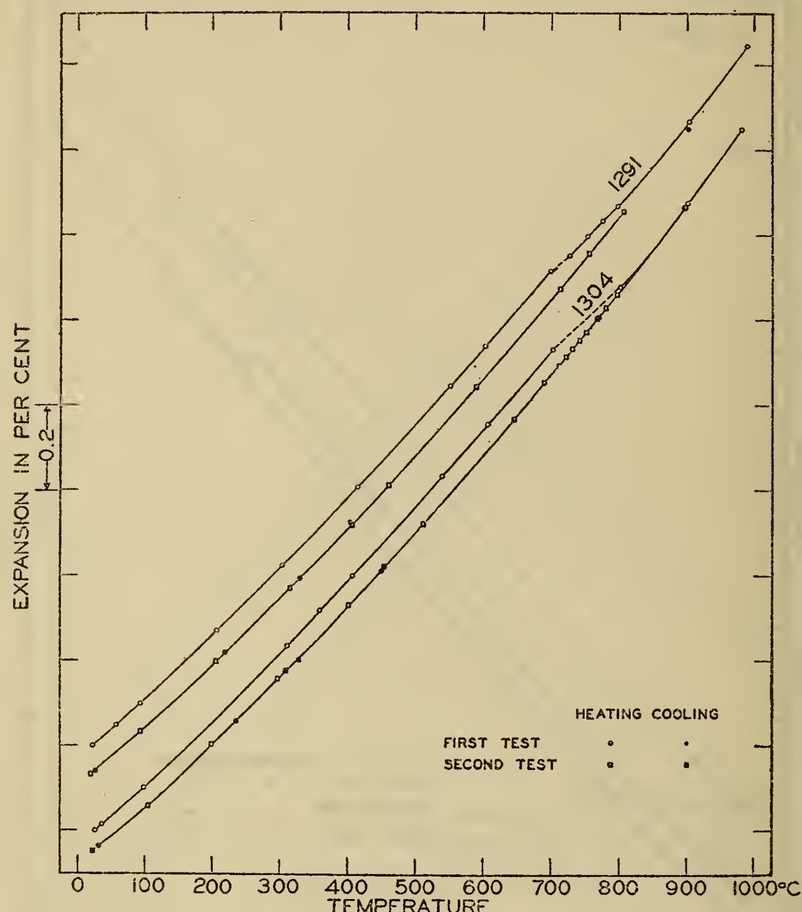


Figure 20.—*Linear thermal expansion of two cast nickel-chromium-iron alloys*

1304, Ni 36.0, Cr 16.4, Fe 45.4, C 0.42, Mn 0.71, Si 1.03 per cent.
1291, Ni 40.3, Cr 21.1, Fe 34.6, C 0.44, Mn 1.43, Si 1.91, Al<0.1, Cu 0.1 per cent.

appreciable amounts of manganese, silicon, and aluminum. The samples during the first heating were in the gamma phase, and the retardation in expansion between 700° and 800° C. was apparently due to the precipitation of excess carbide. The curves on cooling from 1,000° C. to room temperature (first test) show marked expansion from about 100° C. to room temperature, due to a transformation from the gamma phase to the alpha phase.

[25] Data on alloys near the border between regions 6 and 7 will be discussed later.

On reheating sample 1296A to about 700° C. (see second test), the alpha phase changed to the gamma phase. This phase was heated to 1,000° C. and then cooled to about 120° C. At the latter temperature a marked expansion occurred with further cooling to about 50° C., due to a transformation from gamma phase to alpha phase. The alpha phase indicated normal contraction on cooling from 50° C. to room temperature.

Sample 1296A (third test) was then cooled from room temperature to −50° C., heated from −50° to +250° C., and finally cooled to

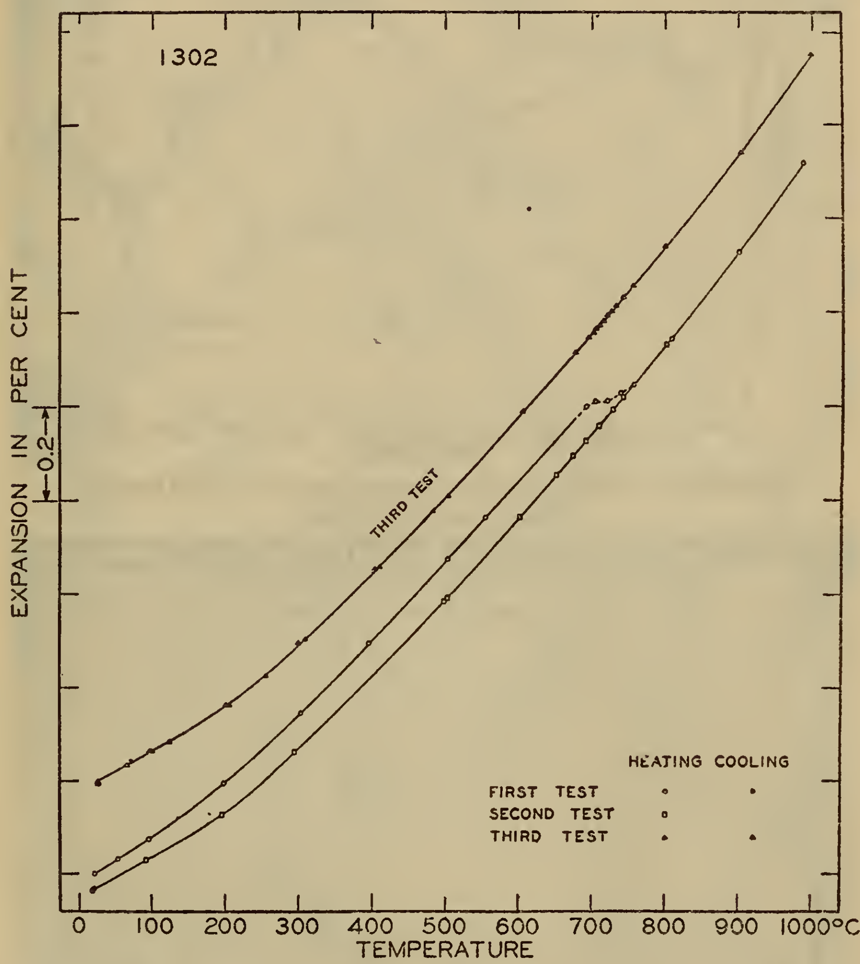


FIGURE 21.—*Linear thermal expansion of cast nickel-chromium-iron alloy*

Ni 41.98, Cr 12.12, Fe 44.10, C 0.43, Mn 0.55, Si 0.81 per cent.

room temperature. The expansion curve does not show a transformation.

The results indicate that the alpha phase for this alloy is stable at low temperatures, and when heated to about 700° C. transforms to the gamma phase. Between room temperature and about 700° C. the alloy may be either in the alpha or gamma phase. Above 700° the alloy is in the gamma phase and, according to Pomey and Voulet, in the delta phase at very high temperatures.

Figure 35 shows the microstructure of sample 1296 as cast and after the second expansion test.

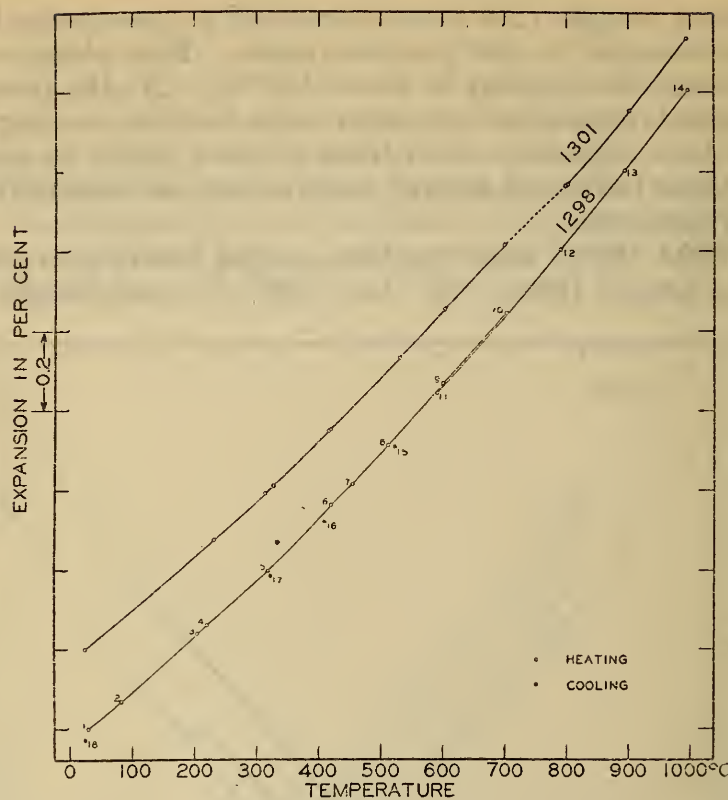


FIGURE 22.—*Linear thermal expansion of two cast nickel-chromium-iron alloys*

1298, Ni 58.07, Cr 19.12, Fe 19.21, C 0.54, Mn 0.94, Si 1.69, Al 0.03, Cu 0.13 per cent.
1301, Ni 65.22, Cr 16.23, Fe 15.33, C 0.59, Mn 1.40, Si 1.18 per cent.

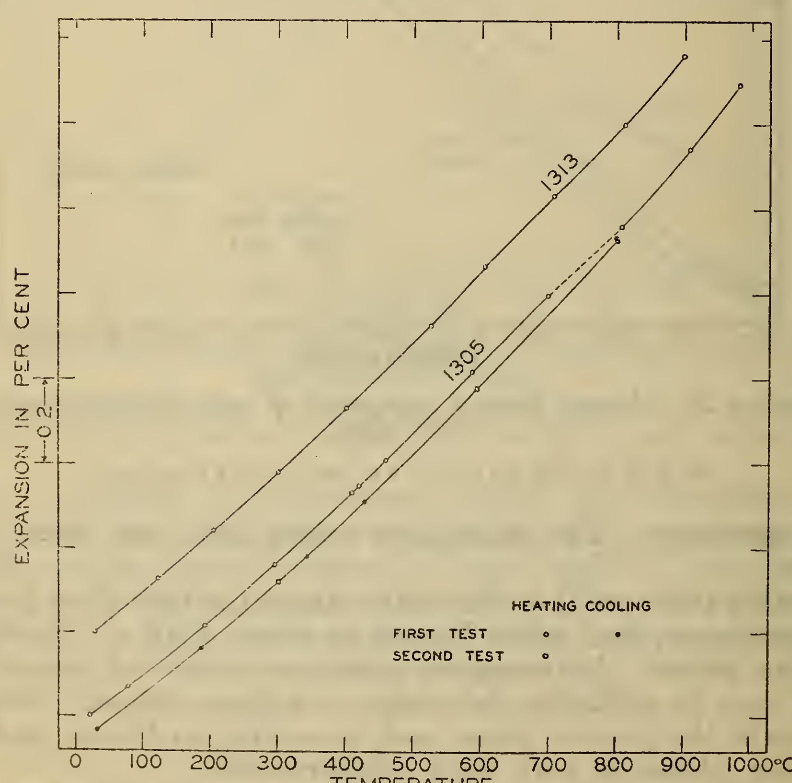


FIGURE 23.—*Linear thermal expansion of two cast nickel-chromium-iron alloys*

1305, Ni 61.00, Cr 15.70, Fe 20.26, C 0.95, Mn 0.62, Si 0.69, Cu 0.78 per cent.
1313, Ni 70.1, Cr 16.3, Fe 6.6, C 0.94, Mn 3.23, Si 2.51, Al<0.1, Cu<0.1 per cent.

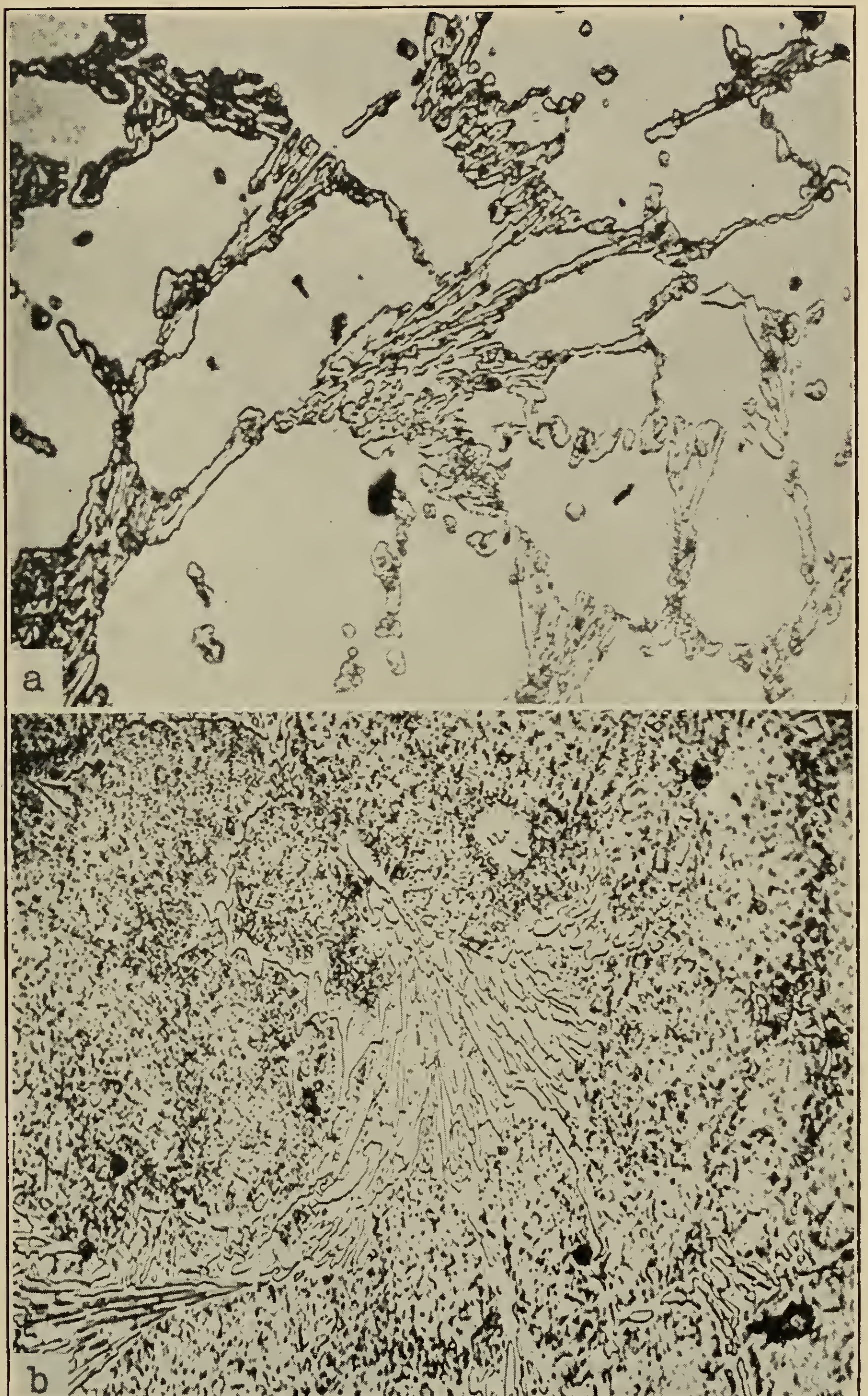


FIGURE 24.—*Microstructure of nickel-chromium-iron alloy (1295).* × *500*

Ni 27.78, Cr 18.50, Fe 50.30, C 0.58, Mn 0.83, Si 1.90, Al 0.08 per cent. *a,* As cast; *b,* after second expansion test.

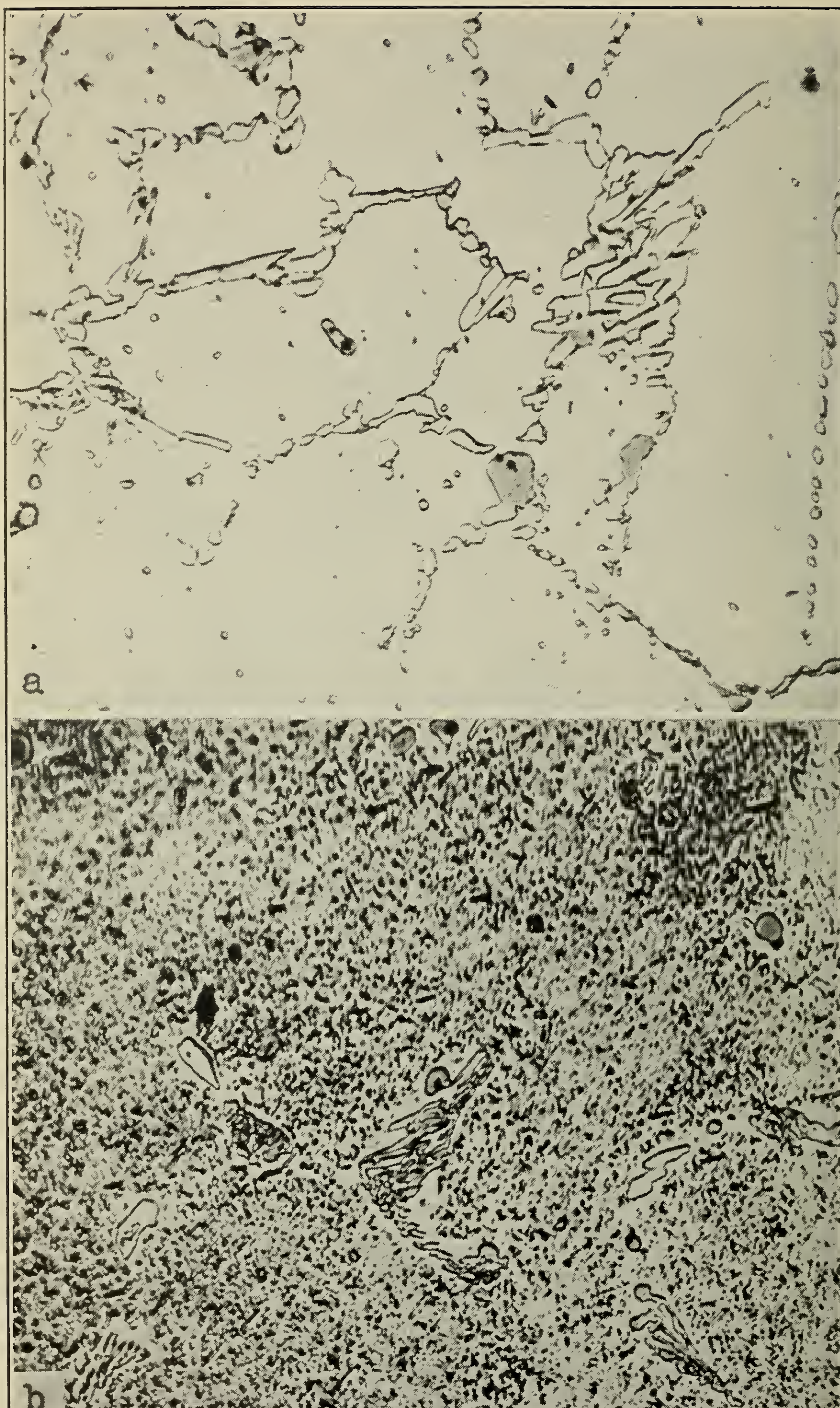


FIGURE 25.—*Microstructure of nickel-chromium-iron alloy (1302).* × 500

Ni 41.98, Cr 12.12, Fe 44.10, C 0.43, Mn 0.55, Si 0.81 per cent. *a*, As cast; *b*, after second expansion test.

FIGURE 26.—*Microstructure of nickel-chromium-iron alloy (1298).* $\times$ *500*

Ni 58.07, Cr 19.12, Fe 19.21, C 0.54, Mn 0.94, Si 1.69, Al 0.03, Cu 0.13 per cent. *a*, As cast; *b*, after expansion test.

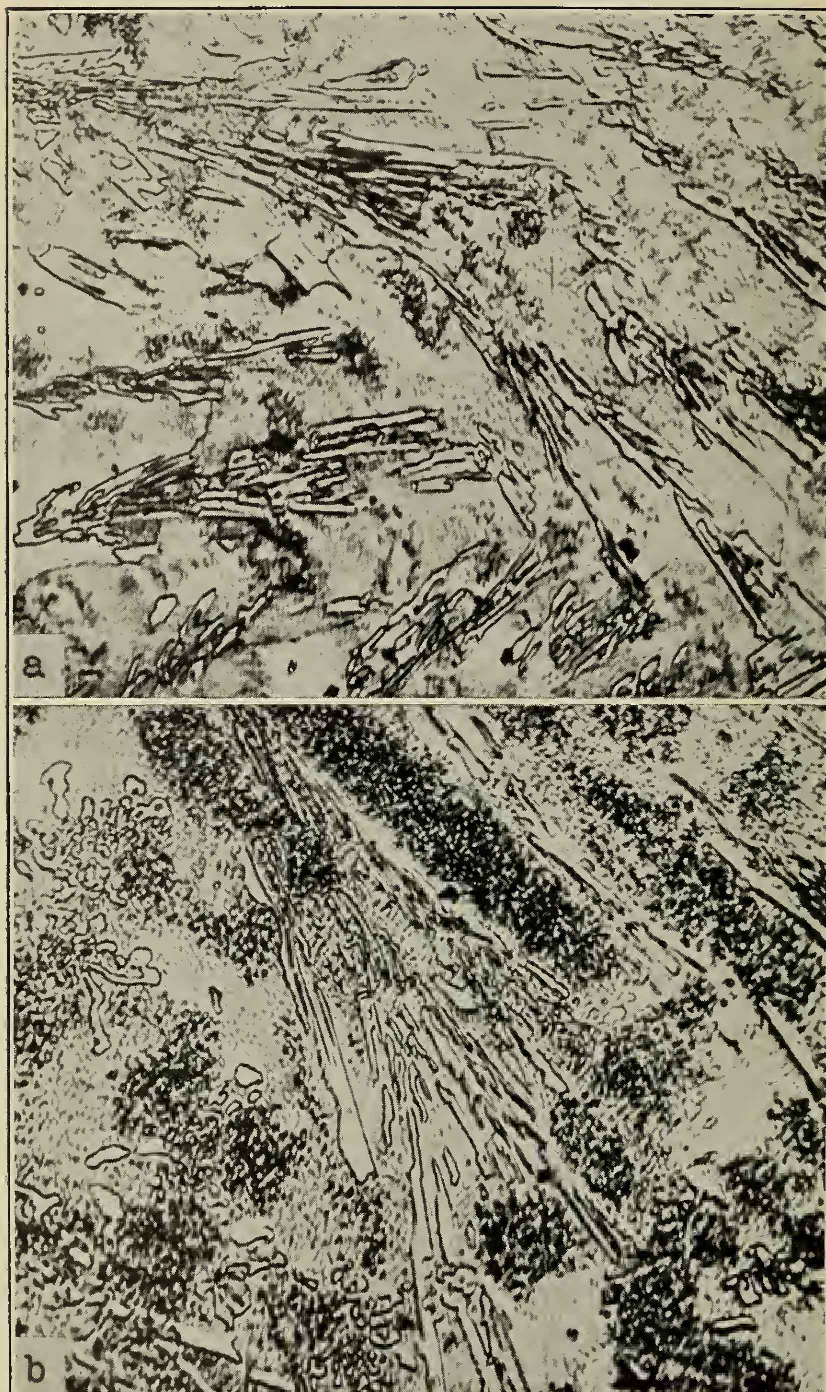



FIGURE 27.—*Microstructure of nickel-chromium-iron alloy (1313).* $\times$ *500*

Ni 70.1, Cr 16.3, Fe 6.6, C 0.94, Mn 3.23, Si 2.51, Al<0.1, Cu<0.1 per cent. *a*, As cast; *b*, after expansion test.

*Regions 6 and 7.*—Alloys 1297, 1418, 1424, 1419, 1311, and 1312 will be grouped together, for they are near the border between regions 6 and 7.

Figure 36 shows the expansion curve of alloy 1297 which was hot-rolled, cooled in brine, annealed and air cooled. This curve indicates retardation in expansion between 700° and 750° C., apparently due to the precipitation of carbide. Figure 37 shows the microstructure of the alloy before and after the expansion test. The relatively small amount of the structurally free constituents (presumably carbide) in the microstructure of this material may be due to the hot working before the expansion test and to the low carbon content.

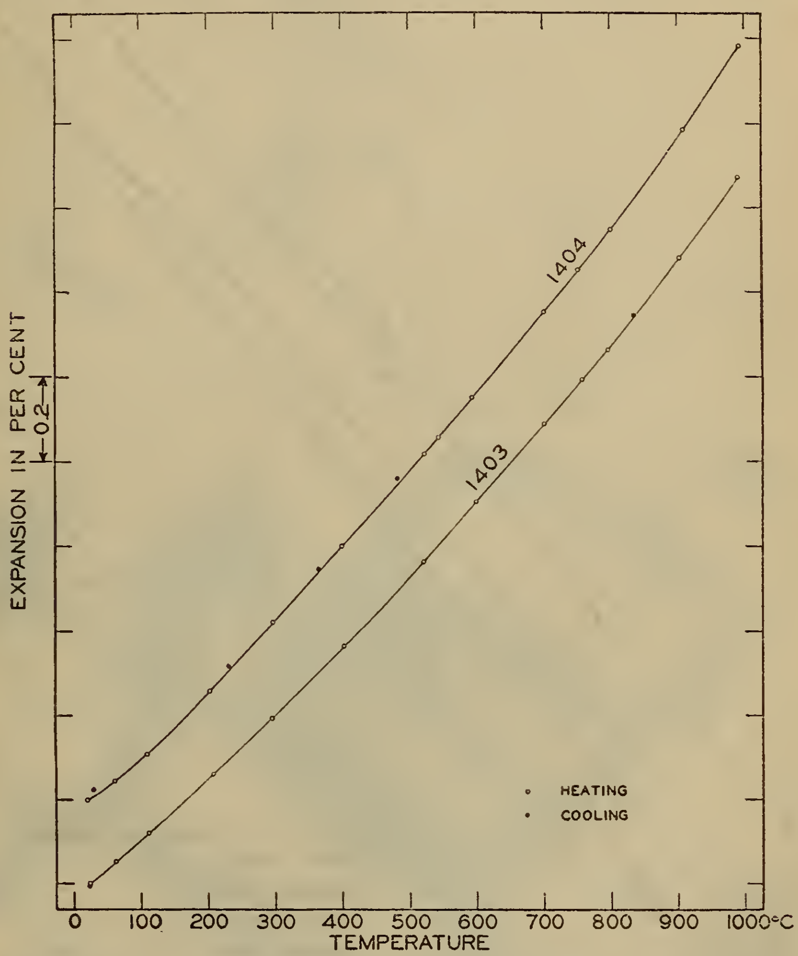


FIGURE 28.—*Linear thermal expansion of two hot-rolled nickel-chromium-iron alloys*

1404, Ni 30.1, Cr 4.9, Fe 63.9, C 0.20, Mn 0.64, Si 0.22, P 0.013 per cent.
1403, Ni 63.0, Cr 15.9, Fe 18.1, C 0.08, Mn 2.14, Si 0.78, P 0.013 per cent.

Figure 38 shows the expansion and contraction curve of sample 1,418 (carbon 0.12 per cent) which was hot rolled and annealed. No critical region was found on heating or cooling between 20° and 1,000° C.

Figure 39 shows the results obtained on the thermal expansion of two quenched alloys (1424 and 1419) containing 0.06 per cent carbon. The expansion curves do not show critical regions.

Figure 40 shows the expansion curves of two alloys (1,311 and 1,312) which were forged and annealed. These curves do not indicate critical

regions. Figure 41 shows the microstructure of sample 1312 after the expansion determinations. The small amount of the structurally-free constituents (presumably carbide) may be due to the hot working before the expansion test and to the low carbon content.

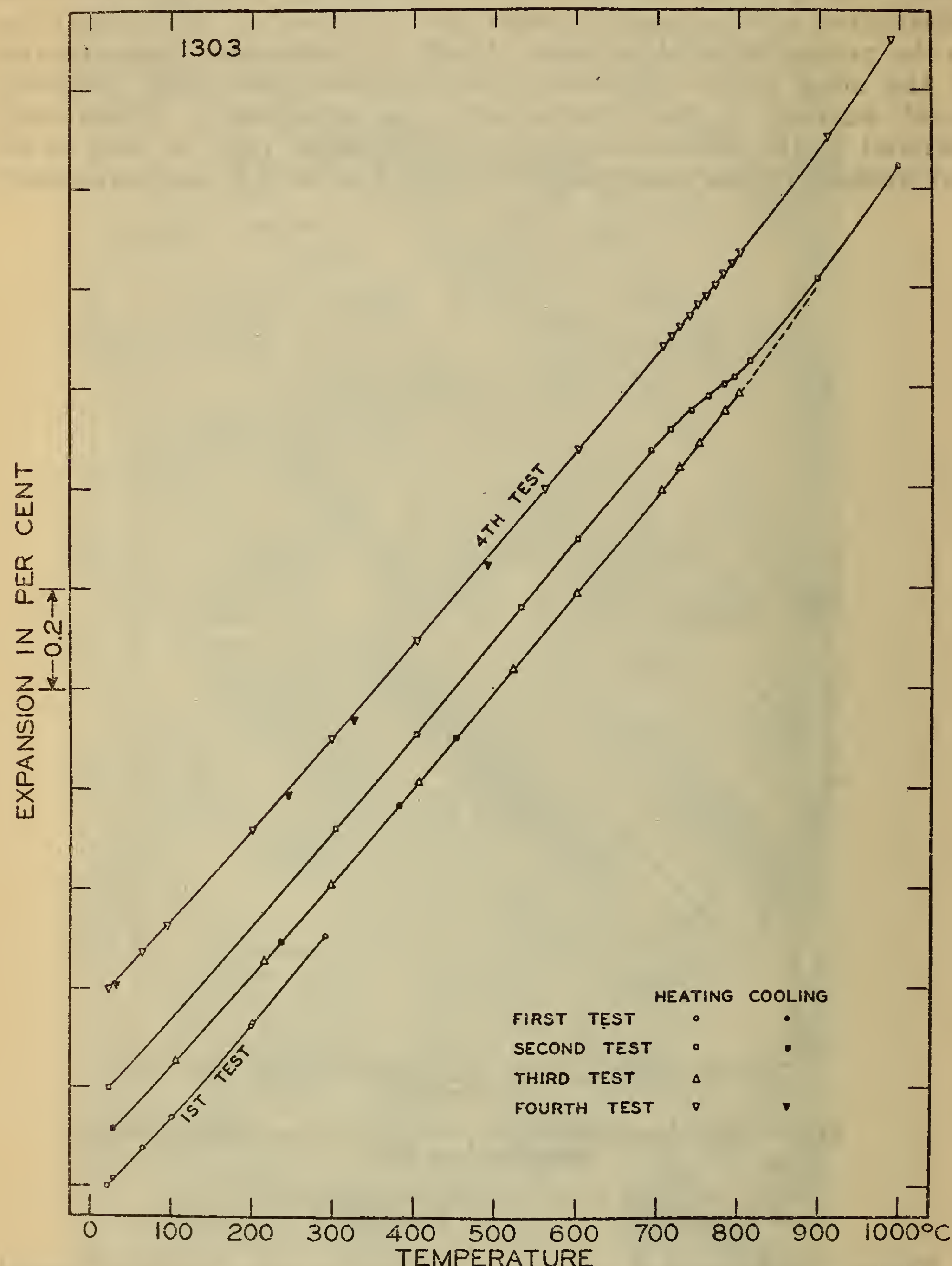


FIGURE 29.—*Linear thermal expansion of cast nickel-chromium-iron alloy*

Ni 19.80, Cr 7.76, Fe 69.30, C 0.49, Mn 0.32, Si 1.03, V 0.46 per cent.

All of these alloys near the border between 6 and 7 appear to be austenitic (gamma phase). The expansion curves between 20° and 1,000° C. do not indicate transformation from this phase to another phase. Data on the thermal expansion of these or similar alloys at low temperatures (below 20° C.) will be necessary in order to determine if there are transformations from the gamma phase to the alpha phase.


FIGURE 30.—*Microstructure of nickel-chromium-iron alloy (1303).* × *500*

Ni 19.80, Cr 7.76, Fe 69.30, C 0.49, Mn 0.32, Si 1.03, V 0.46 per cent. *a*, As cast; *b*, after second expansion test.

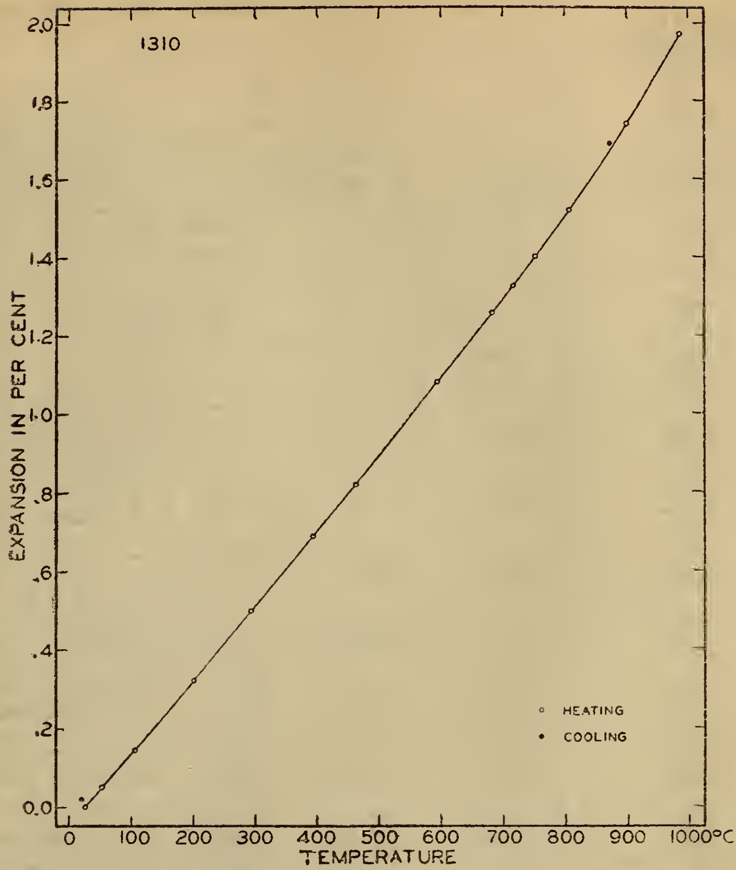


FIGURE 31.—*Linear thermal expansion of forged and annealed nickel-chromium-iron alloy*

Ni 20.2, Cr 7.9, Fe 69.6, C 0.39, Mn 0.74, Si 1.12 per cent.

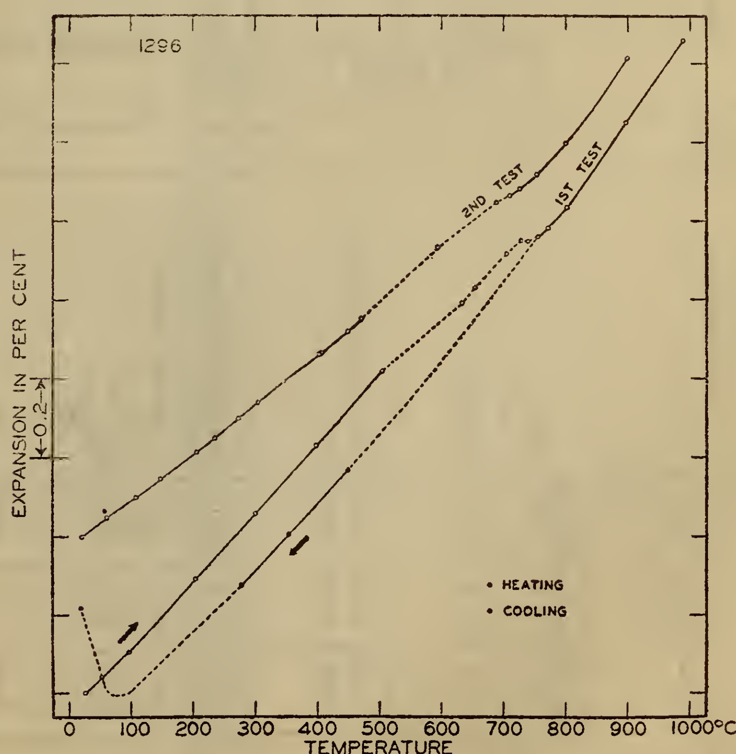


FIGURE 32.—*Linear thermal expansion of cast nickel-chromium-iron alloy*

Ni .41, Cr 21.66, Fe 64.63, C 1.15, Mn 1.16, Si 1.24, Al 1.57, Cu 0.10 per cent.

TABLE 7.—*Average coefficients of expansion of nickel-chromium-iron alloys*

| Sample [1] | Chemical composition: Nickel | Chemical composition: Chromium | Chemical composition: Iron | Heat treatment | Test No. | Phase | Average coefficients of expansion per degree centigrade: 20° to 60° C. | 20° to 100° C. | 20° to 200° C. | 20° to 300° C. | 20° to 400° C. | 20° to 500° C. | 20° to 600° C. | 20° to 700° C. | 20° to 800° C. | 20° to 900° C. | 20° to 1,000° C. | 800° to 900° C. | 800° to 1,000° C. | Change in length due to heat treatment received during test |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Per cent* | *Per cent* | *Per cent* | | | | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | *Per cent* |
| 1314 | 1.3 | 26.7 | 70.0 | Cast | 1 | Alpha | 10.7 | 11.4 | 11.7 | 12.0 | 12.4 | 12.6 | 12.9 | 13.4 | | | | 16.5 | 15.7 | |
| 1314A | | | | do | 1 | do | 10.6 | 11.0 | 11.5 | 11.9 | 12.3 | 12.6 | 12.8 | 13.7 | | | | 16.6 | 16.2 | +0.16 |
| | | | | | 2 | do | | 9.8 | 10.3 | 10.7 | 11.0 | 11.3 | 11.5 | 11.8 | 12.2 | 12.7 | 13.1 | | | +.00 |
| 1411 | 7.5 | 14.0 | 74.7 | Hot-rolled | 1 | Gamma | 16.7 | 16.8 | 17.2 | 17.6 | 17.9 | 18.2 | 18.5 | 18.5 | 18.5 | 18.7 | 19.3 | | | +.43 |
| | | | | | 2 | Alpha | | | | 13.1 | | | | | | | | | | |
| 1411A | | | | do | 1 | Gamma | | | 17.3 | | 18.0 | 18.3 | 18.5 | 18.6 | 18.5 | 18.8 | 19.3 | | | +.53 |
| | | | | | 2 | Alpha, gamma | | 11.9 | 11.9 | 12.1 | 12.4 | 12.6 | | | | | | 21.9 | | +.05 |
| | | | | | 3 | Alpha | | 11.4 | 11.6 | 11.7 | 11.9 | 12.2 | | | | | | | | |
| 1297 | 7.80 | 17.28 | 73.62 | Hot-rolled and annealed | 1 | Gamma | 16.2 | 16.4 | 17.0 | 17.7 | 18.2 | 18.6 | 19.0 | | | | | 22.9 | 24.3 | +.00 |
| 1296 | 8.41 | 21.66 | 64.63 | Cast | 1 | do | 15.5 | 15.2 | 16.3 | 16.6 | 16.9 | 17.1 | | | | | | 22.5 | 22.7 | +.23 |
| | | | | | 2 | Alpha, gamma | 12.0 | 11.6 | 11.7 | 12.1 | 12.1 | | | | | | | 21.6 | | +.02 |
| 1296A | | | | do | 1 | Gamma | 15.4 | 15.4 | 16.0 | 16.5 | 16.8 | 17.0 | 17.3 | | | | | 20.8 | 21.6 | +.25 |
| | | | | | 2 | Alpha, gamma | 11.9 | 11.4 | 11.8 | 12.1 | 12.1 | 12.2 | 12.6 | | | | | 21.4 | 22.2 | +.06 |
| | | | | | [2] 3 | Alpha | 10.8 | 10.8 | 10.8 | | | | | | | | | | | −.01 |
| 1418 | 8.9 | 17.5 | 69.6 | Hot-rolled and annealed | 1 | Gamma | 16.1 | 16.4 | | 17.2 | 17.6 | 17.8 | 18.2 | 18.5 | 18.7 | 19.0 | 19.3 | | | −.04 |
| 1424 | 9.6 | 17.7 | 72.0 | Quenched | 1 | do | 16.4 | 16.5 | 17.2 | 17.7 | 18.1 | 18.3 | 18.6 | 19.0 | 19.5 | 19.7 | 20.0 | | | +.01 |
| 1311 | 9.7 | 19.7 | 69.3 | Forged and annealed | 1 | do | 16.0 | 16.0 | 16.7 | 17.3 | 17.7 | 18.0 | 18.4 | 18.7 | 19.1 | 19.5 | 20.0 | | | +.01 |
| 1312 | 10.4 | 20.7 | 67.5 | do | 1 | do | 15.9 | 16.0 | 16.6 | 17.1 | 17.5 | 17.8 | 18.3 | 18.6 | 18.9 | 19.4 | 19.9 | | | +.02 |
| 1419 | 10.80 | 17.34 | 71.19 | Quenched | 1 | do | 16.4 | 16.7 | 17.1 | 17.6 | 17.9 | | 18.4 | 18.8 | 19.0 | 19.2 | 19.5 | | | −.03 |
| 1306 | 19.55 | 19.55 | 58.93 | Cast | 1 | do | | 15.7 | 16.2 | 16.5 | 16.8 | 17.1 | 17.4 | 17.4 | | | | 19.5 | 20.9 | |
| 1306A | | | | do | 1 | do | 15.8 | 15.6 | 16.1 | 16.5 | 16.8 | 17.0 | 17.3 | 17.5 | | | | 20.1 | 20.9 | −.13 |
| | | | | | 2 | do | | 15.8 | 16.1 | 16.4 | 16.7 | 16.8 | 17.1 | 17.2 | 17.6 | 18.0 | 18.4 | | | +.00 |
| 1303 | 19.80 | 7.76 | 69.30 | do | 1 | do | 17.4 | 17.5 | 13.2 | 18.6 | | | | | | | | | | +.00 |
| | | | | | 2 | do | | | | 18.5 | 18.6 | 18.8 | 18.9 | 19.0 | | | | 19.4 | 21.0 | −.09 |
| | | | | | 3 | do | | 17.7 | 17.9 | 18.2 | 18.4 | 18.5 | 18.9 | 18.8 | 19.0 | | | | | |
| | | | | | 4 | do | 17.6 | 17.6 | 18.0 | 18.2 | 18.4 | | 18.7 | 18.8 | 18.9 | 19.2 | 19.7 | | | −.01 |
| 1310 | 20.2 | 7.9 | 69.6 | Forged and annealed | 1 | do | 18.5 | 18.4 | 18.4 | 18.6 | 18.8 | 18.9 | 19.1 | 19.2 | 19.4 | 19.9 | 20.6 | | | +.03 |
| 1295 | 27.78 | 18.50 | 50.30 | Cast | 1 | do | 15.3 | 15.2 | 15.8 | 16.0 | 16.4 | 16.6 | 17.0 | | | | | 20.1 | 20.1 | −.07 |
| | | | | | 2 | do | | | 15.6 | | 16.2 | 16.5 | 16.9 | 17.2 | 17.5 | 17.8 | 18.3 | | | +.01 |
| | | | | | 3 | do | 15.0 | 14.8 | 15.3 | 15.8 | 16.0 | 16.3 | 16.7 | 16.9 | 17.3 | 17.6 | 18.1 | | | +.00 |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1404 | 30.1 | 4.9 | 63.9 | Hot-rolled | 1 | do | 11.0 | 11.8 | 14.0 | 15.2 | 15.8 | 16.2 | 16.6 | 16.9 | 17.3 | 17.8 | 18.4 | ------ | ------ | +.01 |
| 1304 | 36.0 | 16.4 | 45.4 | Cast. | 1 | do | ------ | 13.8 | ------ | 15.2 | 15.7 | 16.1 | 16.4 | 16.7 | ------ | ------ | ------ | 19.8 | 20.8 | −.04 |
| | | | | | 2 | do | ------ | 12.8 | 14.2 | 14.8 | 15.2 | 15.7 | 16.1 | 16.5 | 16.9 | 17.3 | ------ | ------ | ------ | −.00 |
| 1291 | 40.3 | 21.1 | 34.6 | do | 1 | do | 14.1 | 14.0 | 14.7 | 15.1 | 15.5 | 15.8 | 16.2 | 16.5 | ------ | ------ | ------ | 19.0 | 19.9 | −.06 |
| | | | | | 2 | do | ------ | 13.6 | 14.2 | 14.8 | 15.1 | 15.6 | 16.0 | 16.4 | 16.8 | ------ | ------ | ------ | ------ | ------ |
| 1302 | 41.98 | 12.12 | 44.10 | do | 1 | do | 10.0 | 10.0 | 11.1 | 12.2 | 13.3 | 14.0 | 14.6 | ------ | ------ | ------ | ------ | 20.0 | 20.9 | −.03 |
| | | | | | 2 | do | ------ | 8.7 | 9.1 | 10.8 | ------ | 13.0 | 13.7 | 14.4 | 14.9 | ------ | ------ | ------ | ------ | ------ |
| | | | | | 3 | do | 8.8 | 8.7 | 9.2 | 10.7 | 11.9 | 12.8 | 13.6 | 14.2 | 14.7 | 15.3 | 15.9 | ------ | ------ | −.01 |
| 1298 | 58.07 | 19.12 | 19.21 | do | [3] 1 | do | 13.0 | 13.2 | 13.7 | 13.8 | 14.3 | 14.7 | 15.2 | 15.5 | ------ | ------ | ------ | 19.2 | 19.6 | −.02 |
| 1305 | 61.00 | 15.70 | 20.26 | do | 1 | do | 12.2 | 12.3 | 12.7 | 13.3 | 13.7 | 14.1 | 14.5 | 14.7 | ------ | ------ | ------ | 17.8 | 19.1 | −.04 |
| | | | | | 2 | do | ------ | ------ | ------ | 13.8 | ------ | ------ | 14.4 | ------ | 15.2 | ------ | ------ | ------ | ------ | ------ |
| 1403 | 63.0 | 15.9 | 18.1 | Hot-rolled | 1 | do | 13.2 | 13.4 | 14.0 | 14.4 | 14.8 | 15.2 | 15.7 | 16.0 | 16.3 | 16.8 | 17.0 | ------ | ------ | −.00 |
| 1301 | 65.22 | 16.23 | 15.33 | Cast | 1 | do | ------ | ------ | 13.3 | 13.5 | 13.9 | 14.3 | 14.7 | 15.0 | ------ | ------ | ------ | 18.2 | 19.1 | ------ |
| 1313 | 70.1 | 16.3 | 6.6 | do | 1 | do | ------ | 13.6 | 13.8 | 14.0 | 14.3 | 14.6 | 15.0 | 15.2 | 15.3 | 15.6 | ------ | ------ | ------ | [4] −.05 |

[1] Sample marked A represents duplicate of sample having same number.
[2] Coefficient of expansion is $10.0\times10^{-6}$ between −50° and +20° C. and $11.0\times10^{-6}$ between 20° and 250° C.
[3] Coefficient of expansion between 600° and 800° C. is $18.2\times10^{-6}$.
[4] Value obtained on duplicate sample heated from room temperature to 1,000° and cooled to room temperature.

Table 7 gives average coefficients of expansion of the 26 samples of nickel-chromium-iron alloys in this subsection. The table also indicates the phases (alpha and gamma) of the samples during the expansion tests.

An examination of Table 7 indicates that the coefficients of expansion of the nickel-chromium-iron alloys in the gamma phase are generally larger than the coefficients of the alloys in the alpha phase. The alloys in the gamma phase expand more than the same alloys in the alpha phase for the same temperature range. For the range from 20° to 400° C., the coefficient of expansion in the first heating (gamma phase) of the cast sample 1296 or 1296A is about 40 per cent larger than the coefficient in the second heating (alpha phase). The

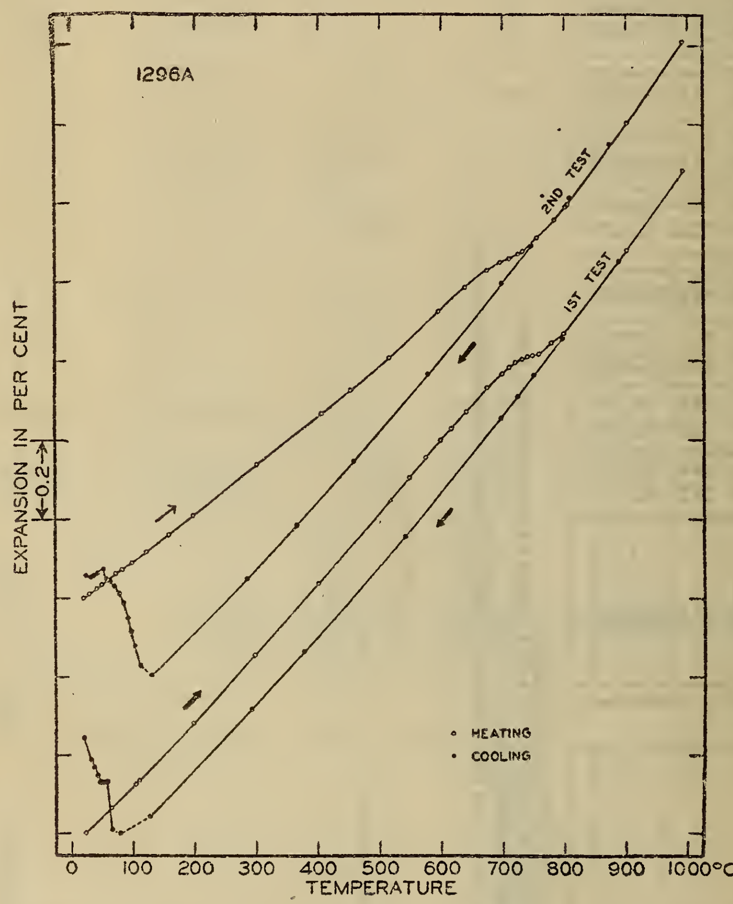


Figure 33.—*Linear thermal expansion of cast nickel-chromium-iron alloy (see fig. 34 for third test)*

Ni 8.41, Cr 21.66, Fe 64.63, C 1.15, Mn 1.16, Si 1.24, Al 1.57, Cu 0.10 per cent.

coefficients of expansion in the first heating (gamma phase) of the hot rolled sample 1411A are approximately 50 per cent larger than the coefficients in the second or third heating (alpha phase) to 500° C. These large differences in expansion were caused by phase changes.

In most cases the coefficients of expansion in the first heating of the cast nickel-chromium-iron alloys are larger than the corresponding coefficients obtained in the second or third heating.

A study of the average coefficients of expansion of the cast nickel-chromium-iron alloys for various temperature ranges indicates that the coefficients of expansion of the cast alloys containing less than 30 per cent nickel are larger than the coefficients of the cast alloys

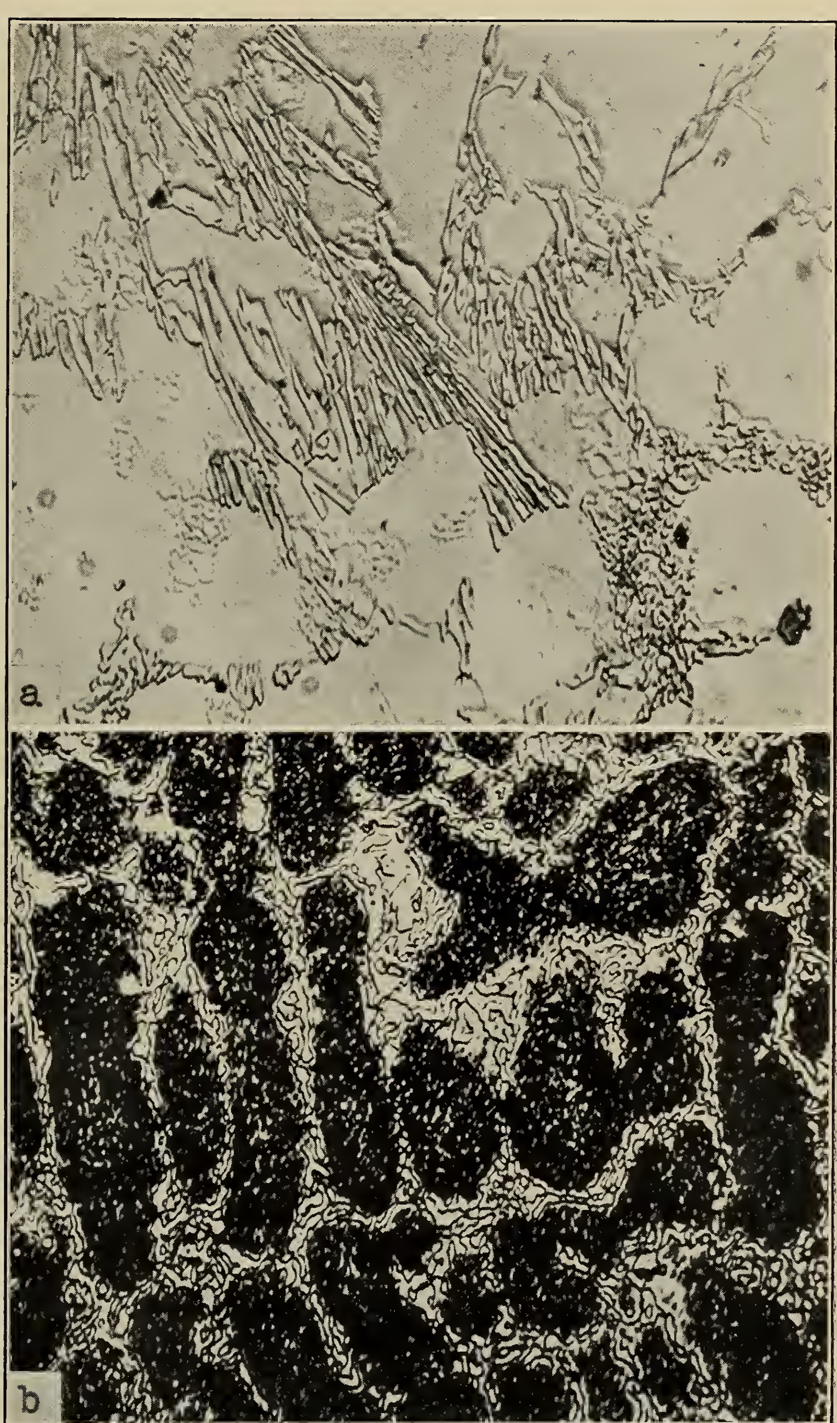


FIGURE 35.—*Microstructure of nickel-chromium-iron alloy (1296).* $\times$ *500*

Ni 8.41, Cr 21.66, Fe 64.63, C 1.15, Mn 1.16, Si 1.24, Al 1.57, Cu 0.10 per cent. *a*, As cast; *b*, after second expansion test.

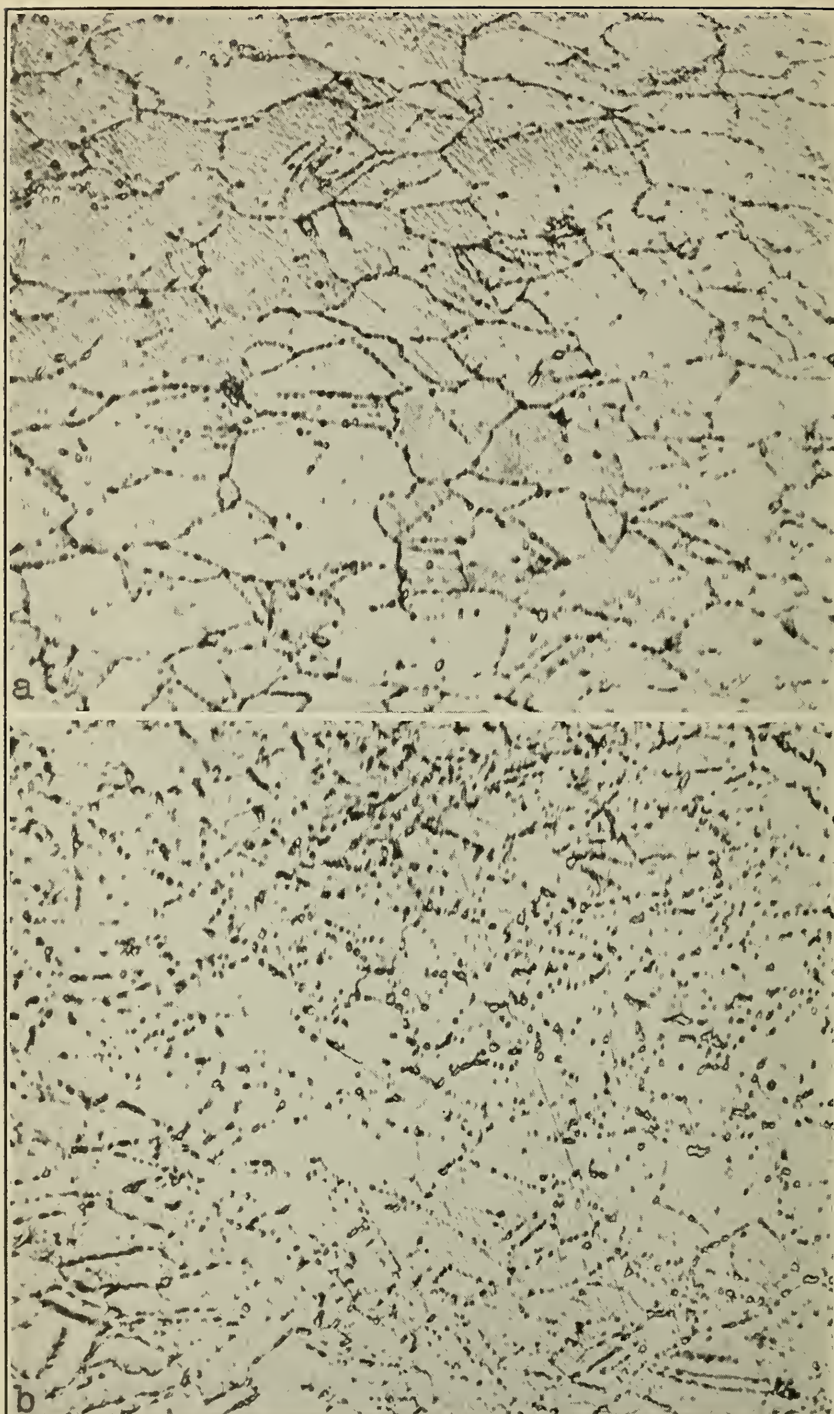


FIGURE 37.—*Microstructure of nickel-chromium-iron alloy (1297).* × *500*

Ni 7.80, Cr 17.28, Fe 73.62, C 0.14, Mn 0.45, Si 0.28, Al 0.18, Cu 0.14 per cent. *a*, Hot-rolled and cooled in brine, annealed at 2,000° F. for one hour and air cooled; *b*, after expansion test.

containing more than 30 per cent nickel. The coefficients of expansion of the former alloys decrease with increase in chromium content, but the coefficients of the latter increase with increase in chromium content.

A similar study of the average coefficients of expansion of the annealed nickel-chromium-iron alloys for various temperature ranges indicates that the coefficients of expansion of the annealed alloys containing from 0 to about 10 per cent nickel increase with increase in nickel content. The coefficients of expansion of the annealed alloys containing from about 10 to 30 per cent nickel decrease with

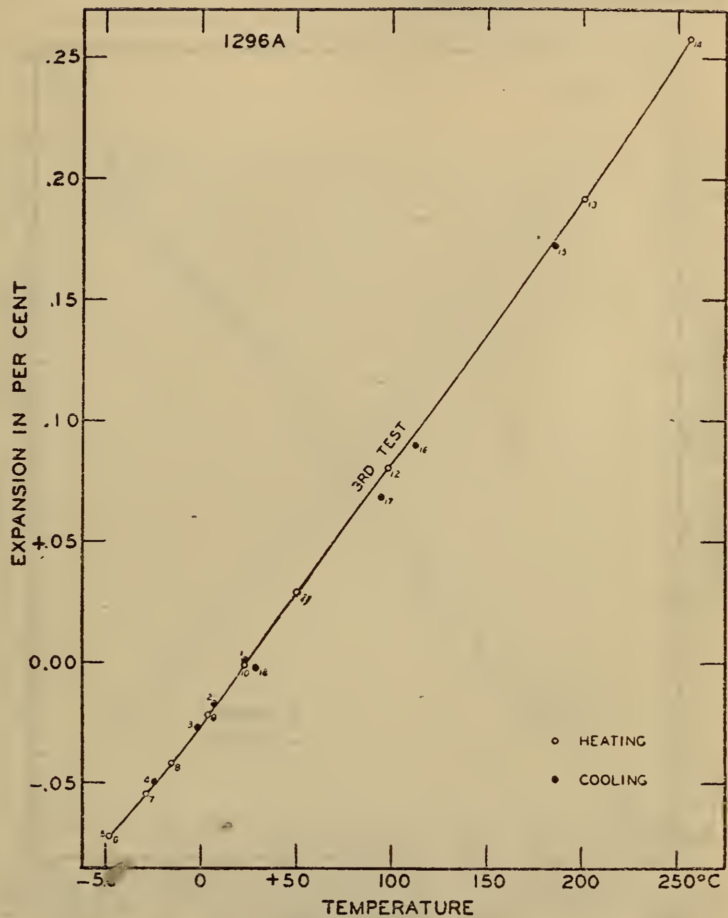


FIGURE 34.—*Linear thermal expansion of cast nickel-chromium-iron alloy at low temperatures (see fig. 33 for previous tests)*

Ni 8.41, Cr 21.66, Fe 64.63, C 1.15, Mn 1.16, Si 1.24, Al 1.57, Cu 0.10 per cent.

increase in chromium content, but the coefficients of the annealed alloys containing more than 30 per cent nickel increase with increase in chromium content.

The coefficients of expansion of the two quenched alloys in Table 7 are slightly larger than the annealed alloys which have the same approximate chemical composition.

## V. CONCLUSIONS

The new data in this paper are useful in several ways: (*a*) It is possible to select heat-resisting alloys which have the same coefficients of expansion for a given temperature range as other materials;

for example, brass, copper, porcelain, steel, etc., when assembled in equipment or appliances where differences in expansion would be unfavorable. (*b*) It is possible to predict the coefficients of expansion of similar new alloys. (*c*) It is also possible to determine the heat treatment suitable for each type of alloy for a specific purpose as governed by the desired structure.

A comparison of the average coefficients of expansion found for the three groups of alloys (nickel-chromium, iron-chromium, and nickel-chromium-iron alloys) investigated is given in Table 8. (For values found for individual alloys reference should be made to the proper sections of the paper.)

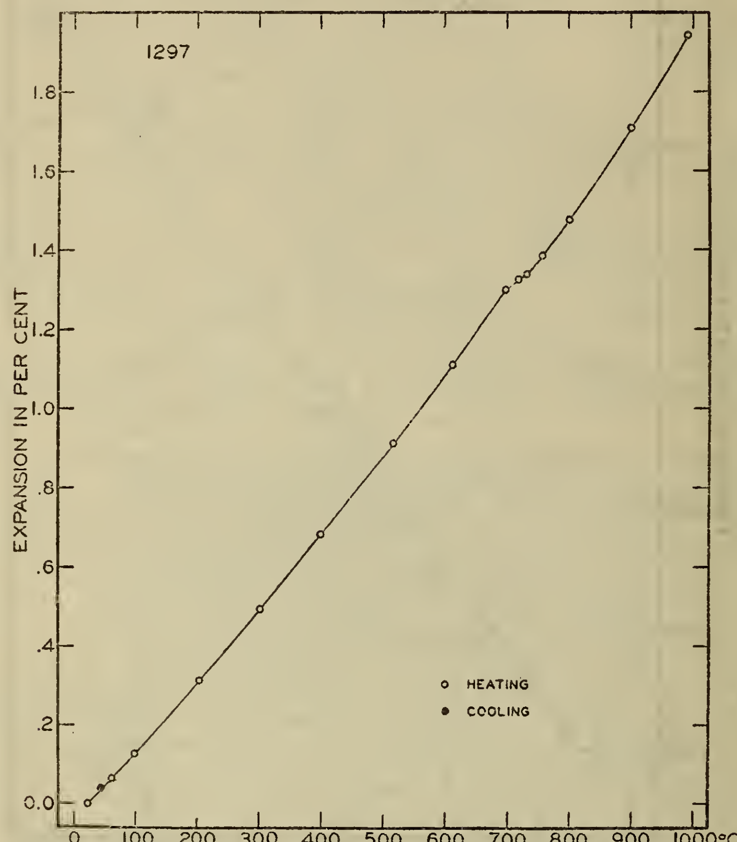


FIGURE 36.—*Linear thermal expansion of nickel-chromium-iron alloy*

Hot-rolled and cooled in brine; annealed at 2,000° F. for one hour and air cooled. Ni 7.80, Cr 17.28, Fe 73.62, C 0.14, Mn 0.45, Si 0.28, Al 0.18, Cu 0.14 per cent.

TABLE 8.—*Comparison of average coefficients of expansion of nickel-chromium, iron-chromium, and nickel-chromium-iron alloys*

| Alloys | Chemical composition | | | Average coefficients of expansion per degree centigrade | | | |
|---|---|---|---|---|---|---|---|
| | Nickel | Chromium | Iron | 20° to 60° C. | 20° to 100° C. | 20° to 200° C. | 20° to 300° C. |
| | *Per cent* | *Per cent* | *Per cent* | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ |
| Nickel-chromium alloys | 76.8–77.0 | 19.3–20.4 | | 13.1–13.8 | 13.0–13.6 | 13.3–14.0 | 13.3–14.3 |
| Iron-chromium alloys | | 17.0–24.6 | 74.0–81.7 | 9.7–10.5 | 10.0–10.6 | 10.3–10.8 | 10.6–11.1 |
| Nickel-chromium-iron alloys | 1.3–70.1 | 4.9–26.7 | 6.6–74.7 | 8.8–18.5 | 8.7–18.4 | 9.1–18.4 | 10.7–18.6 |

TABLE 8.—*Comparison of average coefficients of expansion of nickel-chromium, iron-chromium, and nickel-chromium-iron alloys*—Continued

| Alloys | Average coefficients of expansion per degree centigrade—Continued | | | | | | |
|---|---|---|---|---|---|---|---|
| | 20° to 400° C. | 20° to 500° C. | 20° to 600° C. | 20° to 700° C. | 20° to 800° C. | 20° to 900° C. | 20° to 1,000° C. |
| | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ | $\times 10^{-6}$ |
| Nickel-chromium alloys | 13. 9–14. 5 | 14. 7–15. 1 | 15. 3–15. 7 | 15. 8–16. 2 | 16. 2–16. 7 | 16. 7–17. 2 | 17. 2–17. 8 |
| Iron-chromium alloys | 10. 9–11. 4 | 11. 2–11. 7 | 11. 3–11. 9 | 11. 6–12. 1 | 12. 0–12. 5 | 12. 5–13. 1 | |
| Nickel-chromium-iron alloys | 11. 0–18. 8 | 11. 3–18. 9 | 11. 5–19. 1 | 11. 8–19. 2 | 12. 2–19. 5 | 12. 7–19. 9 | 13. 1–20. 6 |

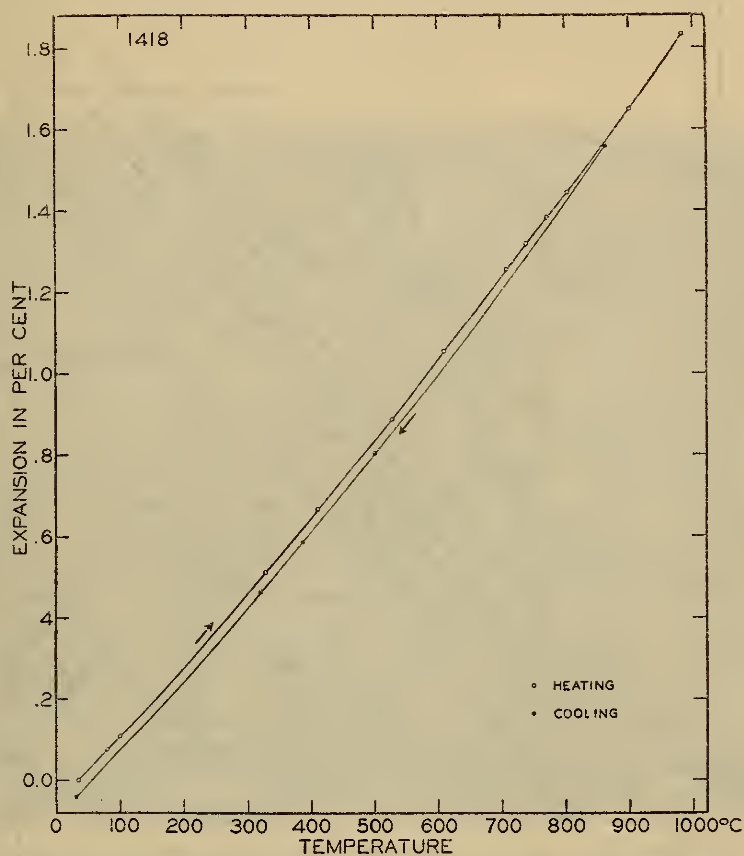


FIGURE 38.—*Linear thermal expansion of nickel-chromium-iron alloy*

Hot-rolled and annealed.
Ni 8.9, Cr 17.5, Fe 69.6, C 0.12, Mn 0.41, Si 0.37, P 0.017, S 0.016, Mo 3.08 per cent.

## 1. NICKEL-CHROMIUM ALLOYS

For a given temperature range, the coefficients of expansion of nickel-chromium alloys containing from 0 to about 20 per cent chromium are nearly the same.

## 2. IRON-CHROMIUM ALLOYS

Critical regions, due to transformations from alpha to gamma phase (austenite), were located. Transformations from alpha phase to austenite occur in carbon-free alloys containing from 0 to about 12 per cent chromium. In alloys containing about 0.05 per cent carbon, the austenite region extends from 0 to approximately 17 per cent chromium. With a carbon content of 0.74 per cent, a transformation

from alpha phase to austenite occurred in an alloy containing 24.6 per cent chromium. Carbon extends the austenite region into the richer chromium alloys.

The coefficients of expansion indicate a tendency to decrease slightly with increase in the chromium content of the iron-chromium alloys containing from 17.0 to 24.6 per cent chromium.

Figure 11 shows the effects of chromium content, carbon content, heat treatment, etc., on the coefficients of expansion of iron-chromium

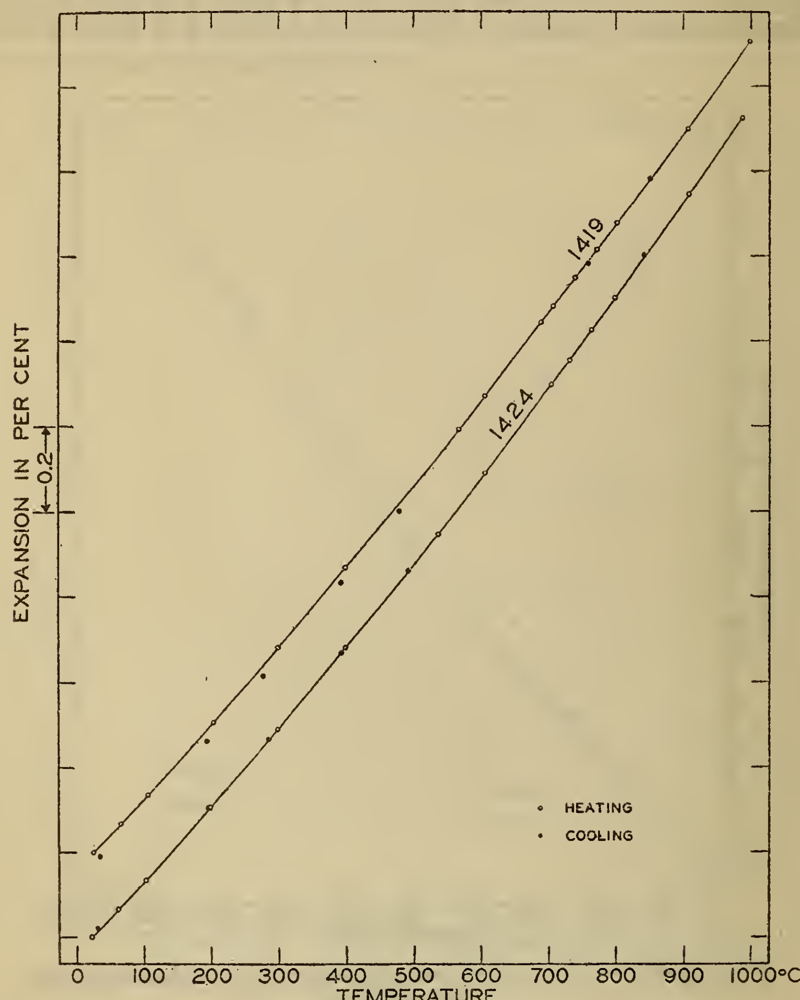


FIGURE 39.—*Linear thermal expansion of two quenched nickel-chromium-iron alloys*

1,424, Ni 9.6, Cr 17.7, Fe 72.0, C 0.06, Mn 0.36, Si 0.28, P 0.016, S 0.012 per cent.
1,419, Ni 10.80, Cr 17.34, Fe 71.19, C 0.06, Si 0.61 per cent.

alloys for various temperature ranges. The coefficients of expansion of annealed alloys (fig. 12) increase with temperature and generally decrease with increase in chromium content. For annealed alloys containing from about 12 to 25 per cent chromium, the changes in the coefficients of expansion are small.

### 3. NICKEL-CHROMIUM-IRON ALLOYS

The results on thermal expansion have been correlated with the structure of the alloys. Transformations from one phase to another caused significant changes in thermal expansion. The coefficients of expansion of the alloys in the gamma phase are generally larger than the coefficients of the alloys in the alpha phase.

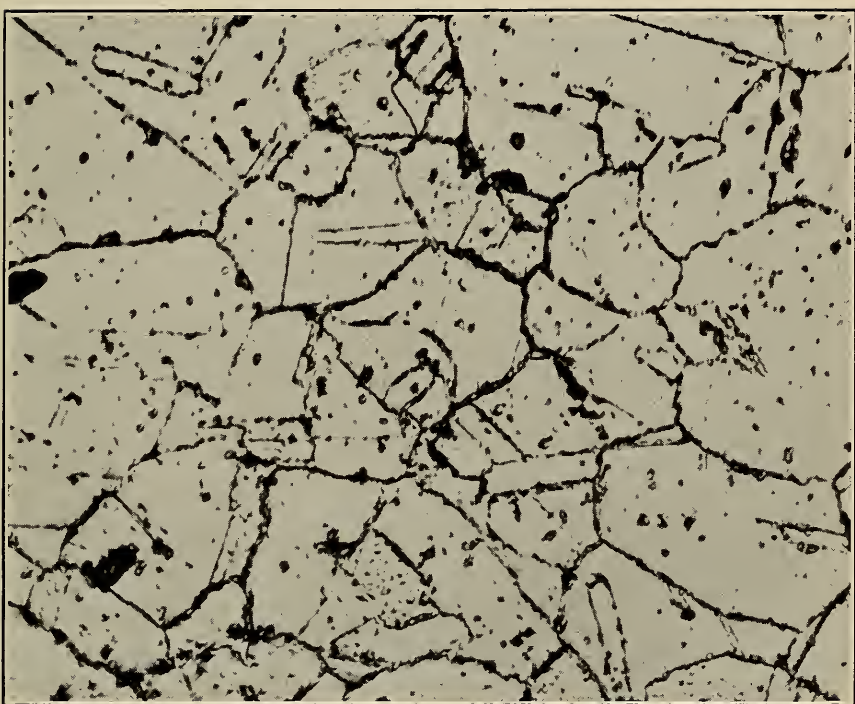

FIGURE 41.—*Microstructure of forged and annealed nickel-chromium-iron alloy after expansion test (1312). × 500*

Ni 10.4, Cr 20.7, Fe 67.5, C 0.18, Mn 0.62, Si 0.56 per cent.

The first expansion curves of nearly all of the cast alloys indicate a retardation or decrease in expansion between 700° and 800° C., apparently due to precipitation of carbide. On repeated heating, these alloys do not show retardation or decrease in expansion, for the alloys appear to be stable after the precipitation of carbide in the first heating. In most cases, the coefficients of expansion in the first heating of the cast alloys are larger than the corresponding coefficients obtained in the second or third heating.

The coefficients of expansion of the cast nickel-chromium-iron alloys containing less than 30 per cent nickel are larger than the coefficients of the cast alloys containing more than 30 per cent nickel.

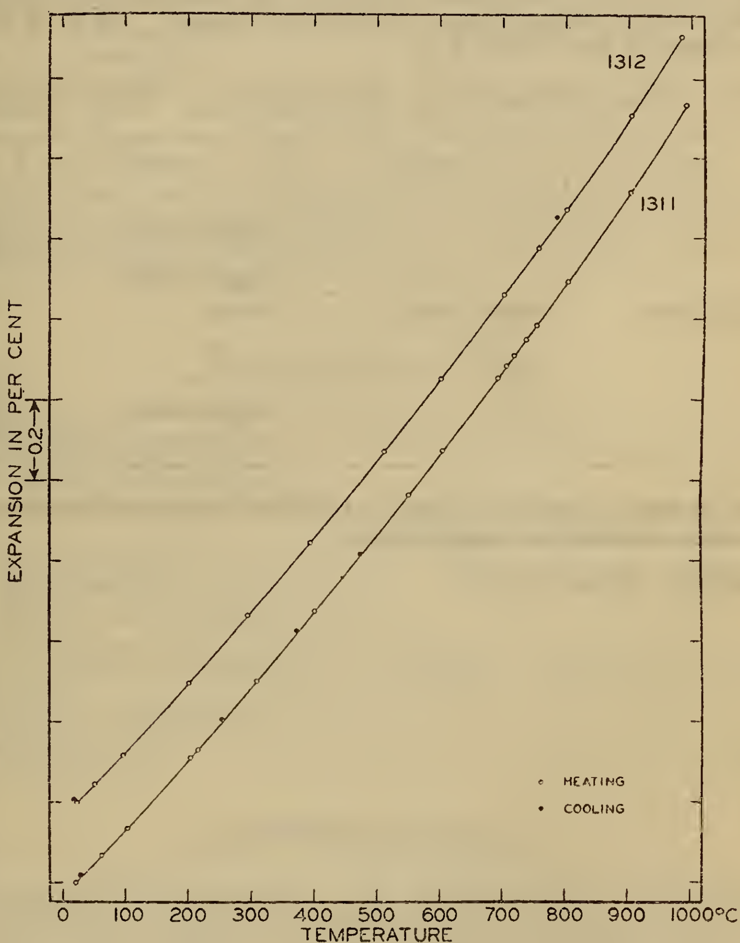


FIGURE 40.—*Linear thermal expansion of two forged and annealed nickel-chromium-iron alloys*

1,311, Ni 9.7, Cr 19.7, Fe 69.3, C 0.21, Mn 0.24, Si 0.89 per cent.
1,312, Ni 10.4, Cr 20.7, Fe 67.5, C 0.18, Mn 0.62, Si 0.56 per cent.

The coefficients of expansion of the former alloys decrease with increase in chromium content, but the coefficients of the latter increase with increase in chromium content.

The coefficients of expansion of the annealed nickel-chromium-iron alloys containing from 0 to about 10 per cent nickel increase with increase in nickel content. The coefficients of expansion of the annealed alloys containing from about 10 to 30 per cent nickel, decrease with increase in chromium content, but the coefficients of the annealed alloys containing more than 30 per cent nickel, increase with increase in chromium content.

## VI. ACKNOWLEDGMENT

The author wishes to express appreciation to G. K. Burgess, H. W. Bearce, W. Souder, L. Jordan, and E. C. Groesbeck, of the National Bureau of Standards, for valuable suggestions, and to H. S. Krider, of the National Bureau of Standards, for assistance in the investigation.

NOTE.—Pieces cut from all of the samples in this investigation were heated in a furnace to 400° C., kept at this temperature for three hours cooled slowly to room temperature and then the surface of each piece was examined. These pieces were successively heated to 500°, 600°, 700°, 800°, 900°, and 1,000° C., and the same procedure was carried out each time. No scale was observed on the surface of any of the pieces which had been heated to a temperature at or below 600° C. At higher temperatures some of the pieces scaled. Table 9 indicates the samples which scaled above 600° C.

TABLE 9.—*Heat-resisting alloys wh ch scaled at elevated temperatures*

| Sample | 700° C. | 800° C. | 900° C. | 1,000° C. |
|---|---|---|---|---|
| 1297 | | | Slightly scaled | Scaled. |
| 1299 | | | | Slightly scaled. |
| 1300, 1300A | | | Slightly scaled | Do. |
| 1303 | Slightly scaled | Slightly scaled | Scaled | Badly scaled. |
| 1310 | | do | do | Do. |
| 1404 | | Scaled | do | Scaled. |
| 1418 | | | | Slightly scaled. |
| 1424 | | | Slightly scaled | Scaled. |
| 1427 | | | do | Slightly scaled. |

The results indicate that the alloys near the iron corner of the ternary diagram in Figure 1 scale at elevated temperatures.

WASHINGTON, June 9, 1931.